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Control Strategies for Using Battery Energy Storage Systems for Grid-scale Enhanced Frequency Response

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ABSTRACT

System frequency is one of the most important power quality factors. Frequency deviations would cause economic losses to the society and damage the generators. The integration of large-scale wind farms into national grids can increase the number of sudden frequency deviations. Moreover, the system inertia would fall because those renewable energy sources (RES) like wind and solar are not able to provide inertia like the conventional generators do. Therefore, it is desirable to find ways of dealing with these undesirable frequency excursions. Battery Energy Storage System (BESS) is a feasible solution to supply a certain amount of electric power and energy in a short time (about 10 times faster than the conventional generators). However, the cost to install and operate a BESS is still expense at this stage. Therefore, it is important to find optimal allocations and sizing of BESSs.

This dissertation describes a study for identifying the optimal frequency regulation within the UK national grid using Battery Energy Storage Systems (BESSs) distributed within the electrical power system. The starting point was historical generation, load and wind forecast data. From this a new dynamic model and simulation has been developed that exhibits the correct dynamic behavior observed in the actual data sets. The new dynamic simulation was then used to optimize the use of distributed BESSs to provide Enhanced Frequency Response (EFR) in the UK national power grid in the presence of large generation/load imbalances caused by variable renewable generation output.

The results of this work show that it is feasible to find a suitable optimal siting and sizing of BESS that can provide frequency response caused by the increasing integration of renewable energy source to meet low carbon obligations in the UK power system. The results also revealed that with the battery energy storage owners could make profit by bidding in to the National Frequency Response service.

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LIST OF MATHEMATICA SYMBLES

C	Future amount of money
C_{di}	Cycles-to-failure at depth of discharge d
C_t	Net cash flow of a year
D	Load-damping constant
E_{Bat}	Remaining capacity of a BESS
f_0	Normalised system frequency
H	System inertia constant
Hi	Inertia constant of synchronous machine i
H_{sys}	System inertia
i	Interest rate for one compounding period
J	Total moment of inertia of the rotor mass
N_{days}	Number of test days
N_i	Number of cycles at depth of discharge d
n	Number of periods
η_{ch}	Battery charging efficiency
η_{dch}	Battery discharging efficiency
Pa	Acceleration power
P_a^w	Wind actual out-turn
P_b	Total balancing requirement
$P_{Battery}$	Total power output of a BESS
$P_{dispatch}$	Output power to supply frequency regulation to maintain SOC
Pe	Electrical power
P_f^w	Half-hourly wind forecast output
Pm	Mechanical power
P_{fast}	Fast cycling components
P_{ss}^i	MW generation of bus i
P_{slow}	Slow cycling components
PV	Present Value
ΔP	Imbalance of generation and demand
ΔP_e	Load change
ΔP_L	Non-frequency-sensitive load change
S_{rated}	System capacity
Si	Rated capacity of synchronous machine i
t	Time in seconds
T	Torque
Ta	Net accelerating torque
Te	Electrical torque output of the alternator
Tm	Mechanical torque supplied by the prime mover
W	Total battery life fraction consumed estimated for different cycle ranges i
ω_r	Rotational angular velocity

ω_m	Machine rotational angular velocity
θm	Angular position of the rotor with respect to a stationary axis

LIST OF ABBREVIATIONS

ACE	Area control error
AGC	Automatic generation control
BESS	Battery energy storage system
BM	Balancing mechanism
CAES	Compressed air energy storage
CCGT	Combined cycle gas turbine
DG	Distributed generator
DOD	Depth of discharge
DSM	Demand side management
EAA	Equivalent annual annuityED Economic dispatch
EFR	Enhanced Frequency Response
ESS	Energy storage system
FCDM	Frequency Control by Demand Management
FERC	the United States Federal Energy Regulatory
LCO	Lithium cobalt oxide
LCOE	Levelised cost of energy
LCO-NMC	LCO-lithium nickel manganese cobalt oxide composite
LFC	Load frequency control
NGET	National Grid Electricity Transmission plc
O&M	Operation and Maintenance
PV	Photovoltaic
REM	Regulation energy management
RES	Renewable energy sources
RoCoF	Rate of change of frequency
SHETL	Scotland and Scottish Hydro Electric Transmission Ltd
SMES	Superconducting magnetic energy storage
SNSP	Non-synchronous penetration
SO	System Operator
SOC	State of charge
SPT	Scottish Power Transmission Limited
SPM	Service performance measure
STOR	Short term operating reserve
TSO	Transmission System Operator
UPS	Uninterrupted power supply

CHAPTER 1: INTRODUCTION

1.1 Introduction and Background

Climate change is becoming one of the most challenging problems in the human society. At the same time, running short of non-renewable energy sources, such as fossil fuel, gas, prompts people to look for a sustainable path of development. One of the paths to mitigate climate change and save the non-renewable energy sources is to encourage electricity generators to produce electricity by using renewable energy sources, such as wind and solar. In the UK, one of four Future Energy Scenarios published by National Grid is called 'Two Degrees'. The Two Degrees scenario aims at meeting the UK's carbon reduction target by 2050 and anticipates that the renewable generating capacity would increase to as much 60% in the power system [1].

However, introducing a large amount of renewable energy sources (RES) to the power system is a huge challenge for the System Operator to assure the power quality. Although renewable energy sources are sustainable and can reduce greenhouse gas emissions, they also have shortcomings. In most cases, renewable generation is non-controllable, variable and unpredictable [2]. Most conventional generators used to produce electricity are synchronous machines that convert kinetic energy of a rotating mass to electrical energy, or vice versa. Synchronous machines could provide system inertia [3]. Asynchronous machines, such as variable speed wind turbines, do not supply system inertia. Although the improvement of wind turbine manufacturing technologies allow wind turbines to provide synthetic inertia via releasing stored kinetic energy, the frequency will still experience a recovery period. Sometimes the frequency drops further and cause a more severe event due to this recovery period. Thus, the increasing penetration of RES means that the frequency would be harder to maintain with the same amount of generation and demand imbalance. Moreover, this situation would be worse since, for example in the UK, the allowance for infeed loss has increased from 1320MW to 1800MW, so that the offshore generation with a capacity up to 1800MW can be connected via a single cable [4].

Matching supply and demand is a challenging task and it is not possible in the real world. The reason for this is that it is not possible to predict the exact behavior of the participants in the power system, neither the consumer nor the generator. Consumers could decide to turn their lights on and off whenever they want to. Although several technologies have been proposed to predict the behavior of consumers, 100% accuracy is not possible. For the generators, sometimes they have to decrease their output for a technical problem. A sudden loss of generation is possible especially for those renewable power. Renewable power plants are highly depend on the weather. For example, if the wind is not strong in the area of wind power plant, then we are not able to generate the amount of wind power that is supposed to be generated. This leads to a shortage of electricity. Or in some cases, the wind is too strong so that we have to stop generating electricity to protect wind turbines. Typically, the actual wind out-turn is lower than the day-ahead forecast [5]. Thus it is neither possible to predict the exact generation nor the demand in the power system. Employing technologies to balance the supply and demand is necessary.

The generation and demand mismatch could be mitigated either from the demand side or the generation side. One of the expected solutions from the demand side is demand side management (DSM). DSM involves initiatives and technologies trying to modify the consumer demand. Although it has been indicated that DSM could not only reduce the generation margin, improve transmission network investment and operation efficiency, but also manage demand-supply balance in systems with renewables [6]. Implementation of DSM is highly reliant on advanced metering, communications, control methods and information technologies, while these are still in the early development stage. Moreover, for those large wind or solar power plants, demand side management is not enough to match the generation with the local demand and modifying the demand from places far away is not competitive compared with conventional method, such as regulating the output of conventional generators.

Thus the regulation from the transmission side is necessary.

One of the promising methods to balance the supply and demand is by employing energy storage systems. Previous works [7] [8] have demonstrated the use of energy storage system to regulate system frequency. Among various types of energy storage systems, Battery energy storage systems (BESSs) have the ability to maintain the system frequency with faster response and higher efficiency than conventional generators. According to [9], LiFePO4 battery technology stands out because of its relatively high energy and power capacity. Present statistics show that BESS unit prices have come down to about 444 £/kWh [10]. A further reduction is expected to be seen with the further development of battery technology, an example of Lithium-ion batteries price falls is shown in Fig 1. However, the cost of batteries is still a barrier to making battery energy storage systems competitive with conventional generators. The effectiveness of BESSs is dominated by its usage compared to capital costs. Load and generation profiles vary from site to site, thus the sizes and locations of BESSs should be carefully decided.

In recent publications, different methods have been proposed to investigate the optimal size of a grid-scale BESS to supply frequency regulation [11]. The allocation of BESSs from the perspective of voltage regulation was investigated in [7]. Reference [7] proposed a methodology to decide the optimal allocations and sizes of BESS in the system to improve voltage profile considering the energy losses and the total cost associated with distributed generator (DG) or a BESS of a particular type. However, this work does not consider the dynamic performance of BESSs to provide frequency response, which cannot indicate the degree of improvement of frequency by using BESSs, which could be an import utilisation of BESS in the power system.

In this report, the UK network is represented as a dynamically equivalent 12-bus system with wind power connected. The BESSs are responsive to the forecasting error and a general operation strategy of BESS is implemented within this dynamic system model. Furthermore, the Equivalent Annual Annuity (EAA) of the BESS's installation at different locations is evaluated.

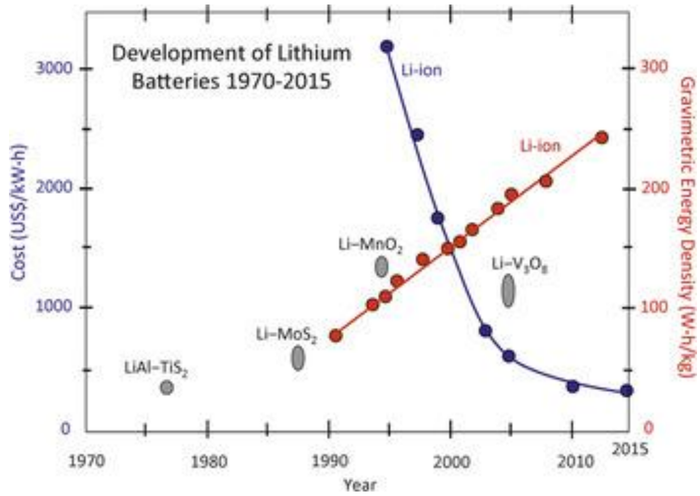


Fig. 1 Development of battery price: Lithium-ion batteries and beyond [12].

1.2 Research Questions and Objectives

The purpose of this study is to find the optimal method for siting and sizing of BESS to provide frequency response. The main research objectives are:

1. Review and evaluate the suitability of potential applications of BESSs in the power system.
2. Identify a reasonable balancing requirement of frequency regulation for BESSs and conventional generators, respectively.
3. Evaluate the impact of RES penetration on the power system stability.
4. Analyse the potential impact of employing grid-scale BESSs on the power system operation, leading to siting and sizing optimisation.

1.3 Statement of Originality

In recent publications, different methods have been proposed to investigate the optimal size of a grid-scale BESS to supply frequency regulation [11]. The allocation of BESSs from the perspective of voltage regulation was investigated in [7]. There is little in the literature that considers the locations of grid-scale BESSs supplying frequency regulation with respect to their sizes to obtain an optimal effect.

The contributions made by this study can be summarized as follows:

i. New system model: By introducing the transmission network's effect in a dynamic system model, the BESS could response to the nearest dynamic generation/load fluctuations, thus minimize the transmission losses. This new dynamic model provides a platform to practice different optimisation methodologies and power system performances evaluations applied to various system services.

ii. New assessment algorithm: Application of the proposed methodology to evaluate the value of BESS at different locations within the transmission network can be applied to a range of other frequency response services.

1.4 Thesis Organization and Outline

To fulfill the objectives and answer the research questions, the body of this thesis is divided into several chapters, and is organized as follows:

Chapter 2 gives a brief introduction of Energy Storage System (ESS) services in the power system and the state of art of applicable battery technologies. Balancing services defined by National Grid are introduced in detail.

Chapter 3 introduces power system stability analysis in relationship with frequency regulation and shows dynamic model of conventional power plants that participant in frequency regulation in response to supply-demand imbalance.

Chapter 4 proposes a method for cooperation between conventional generators and battery energy storage system to supply frequency regulation and demonstrates the modeling of battery energy storage systems.

Chapter 5 shows simulation results employing battery energy storage systems in cooperation with conventional generators to supply frequency response in different areas. Economic analysis is then demonstrated by using equivalent annual annuity evaluation.

Chapter 6 summarizes the main outcomes and conclusions achieved in this study.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction of ESS and ESS services

This section presents energy storage technology applications in power systems. Energy storage system applications are normally categorised by their connection points in the network. They can be divided into transmission-connected energy storage, distribution-level energy storage and demand-side energy storage as shown in Table 1 or they can simply be divided into utility applications and end-user applications [8] [13]. Each application has specific technical requirements for storage systems ranging from their capacities to response rates which can significantly vary from each application. Thus this report will focus on transmission-connected energy storages for the grid utilisation. The key applications at the transmission level are introduced in Table 1 and a summary of technical requirements of these services is shown in Fig 2. In Fig 2, these comparisons are very general, intended for conceptual purposes only. Many of the storage applications have varied duration and power ranges.

Table 1 Electricity grid energy storage services [14]

Use Case	Categories
Transmission-Connected Energy Storage	Bulk Storage System
	Ancillary Services
	On-site Generation Storage
	On-site Variable Energy Resource Storage
Distributed-Level Energy Storage	Distributed Peaker
	Distributed Storage Sited at Utility Substation
	Community Energy Storage
Demand-Side (customer-sited) Energy Storage	Customer Bill Management
	Customer Bill Management w/Market Participation
	Behind the Meter Utility Controlled
	Permanent Load Shifting
	EV Charging

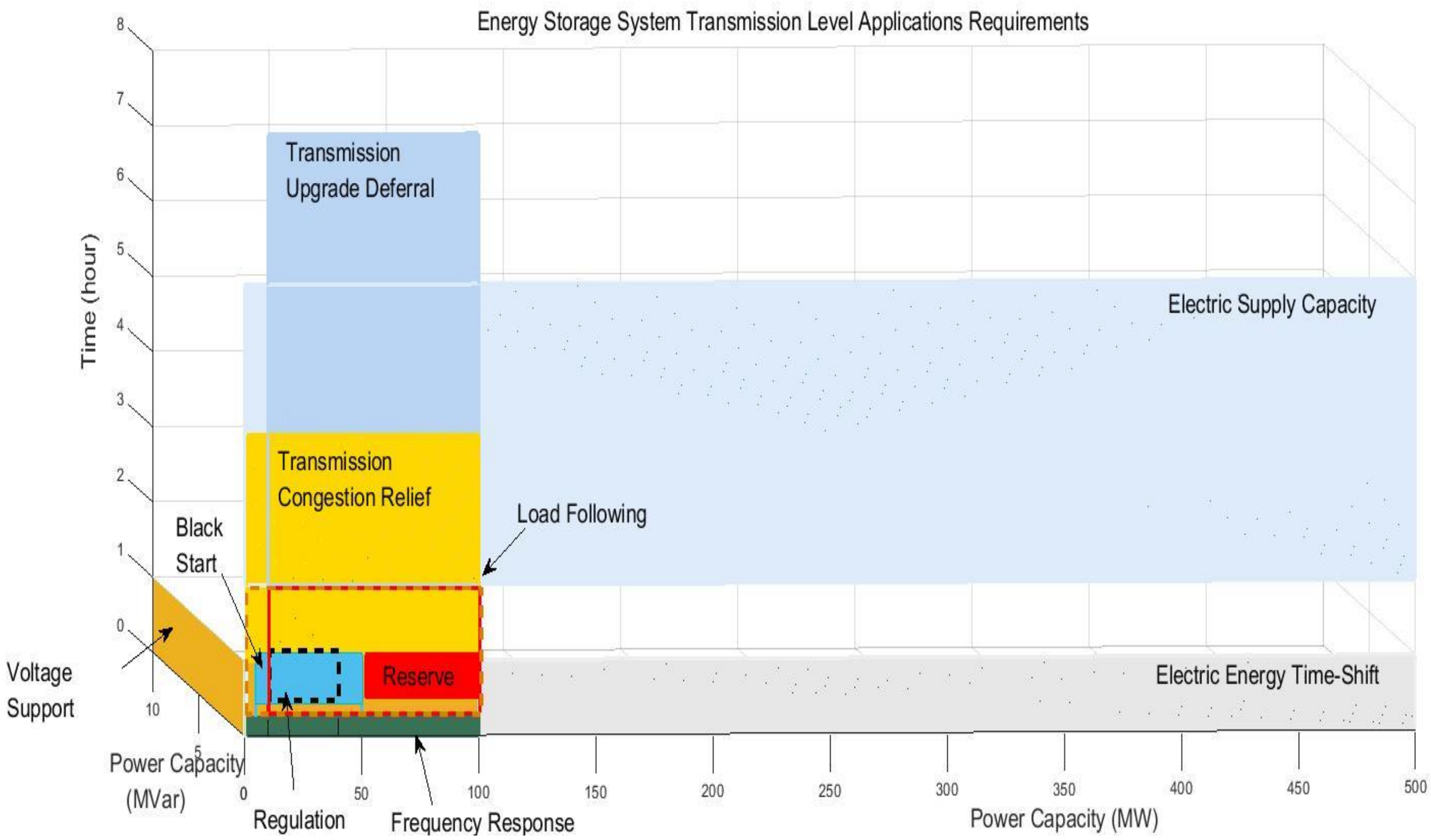


Fig. 2 Technical requirements of ESS at transmission level [9]

2.1.1 Bulk Energy Services

Initially, the energy storage concept was widely used for time-shifting energy either in order to store off-peak electricity at a lower price or to provide peaking energy at a higher price to arbitrate, or to store the excess energy produced by uncontrollable renewable energy sources to avoid a power curtailment. The most commonly used and major storage that exists today is pumped hydro facilities greater than 200MW [14]. However, if used for renewable generation, storage capacities depend on the size of the wind plant or solar plant that they are connected to. Basically, a small-scale renewable power plant will require less storage capacity than a large-scale power plant. Thus the range of capacity requirement could be large, which means more energy storage technologies can support this application. Storage systems used to relieve the generation burden, or the need to build new generating capacities, to supply peaking energy will have specific requirements for energy capacity, which depends on the discharge duration. The energy capacity is affected by the way that generation capacity is priced.

2.1.2 Ancillary Services

According to the United States Federal Energy Regulatory Commission (FERC), ancillary services are defined as anything that can support the transmission of electric power from generator to consumer to maintain reliable operation of the interconnected transmission system [15]. Figure 3, demonstrates a brief relationship between ancillary services that BESS can supply with respect to the service time scale. For example, the requirement for assets to provide primary frequency control is to response to a frequency event in 10 seconds. For secondary frequency control, assets providing this service need to adjust their power output to the required level in 30 seconds and maintain the output for minutes until notified by the System Operator.

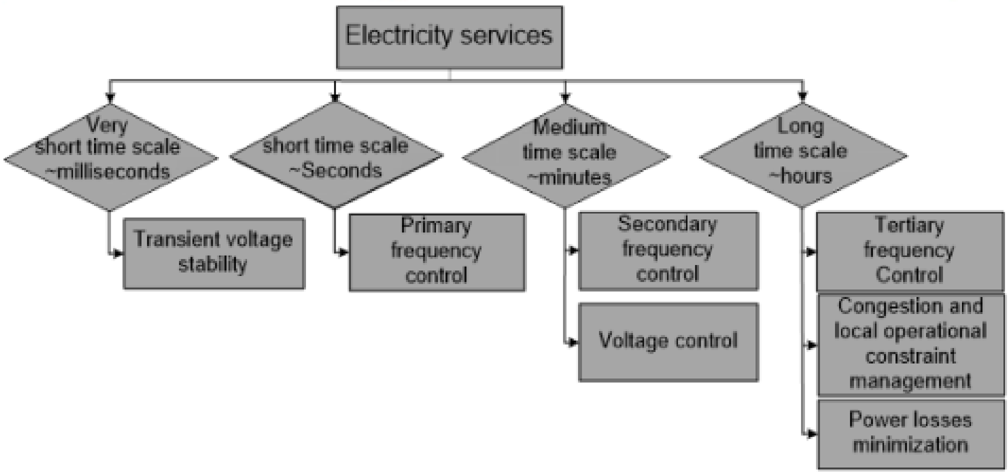


Fig. 3 Electricity services provided by BESS [16].

2.1.2.1 Regulation

The frequency regulation, also referred to as load-frequency control (LFC), described here is based on the American power system. Area control error (ACE) was introduced to return the steady-state frequency error, Δf, back to zero after an event and in the meantime maintain the net tie-line power out of the area at its scheduled level [17]. Generators online will adjust their outputs to reduce the difference caused by generation and load fluctuations. Energy storage systems can help provide down regulation by discharging electricity and up regulation by absorbing electricity while mitigating the wear and tear of the thermal generators.

Load-frequency control (LFC) combined with economic dispatch (ED), which minimises the operating cost in an area, sets up the automatic generation control (AGC) strategy. However, AGC is not employed in the UK and this part of the job is replaced by manual control obligated by the system operator National Grid. The method implemented in order to maintain the system stability is worth considering so as to imitate the behavior of system operators.

2.1.2.2 Reserve

Reserve discussed here is referred to as the secondary response and tertiary response in other countries. In the UK, the reserve service consists of Balancing Mechanism (BM) Start-up, short term operating reserve (STOR), demand management and fast reserve characterized according to different timescales required to be ready to provide the service ranging from 2 minutes to 240 minutes as illustrated in Fig.4. This is the additional power sources available to National Grid in the form of either generation or reduced demand when an unexpected generation unavailability or demand increase occurs.

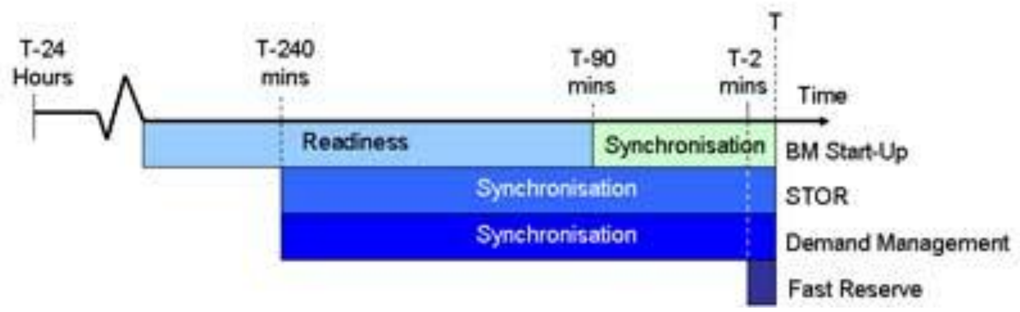


Fig. 4 Different sources require different timescales to deliver the services [3].

Unlike generators, energy storage does not necessarily have to be online or operational, they just need to be able to discharge when instructed.

2.1.2.3 Voltage Support

It is of importance to not only keep active power but also reactive power in balance. Both utility and customer equipment is designed to operate at certain voltage levels. Thus voltages outside the allowed range will affect performance and even damage equipment [3]. Voltage support helps the transmission system to minimize RI^2, XI^2 losses and obtain its maximum utilisation. This service is normally performed by synchronising generators with automatic voltage regulators and compensating devices to produce or absorb reactive power. Energy storage systems can also supply or absorb reactive power to offset the reactances in the system. They can replace designed generation plants that supply reactive power within the grid in a central location.

2.1.2.4 Black Start

Energy storage system can also provide black start service by providing active power to energise the transmission lines and bring power plants on line when a total or partial shutdown of transmission system occurs. The capabilities required by this service include the ability to start up the main generating plant of the station from shutdown independently and be ready to energise the transmission system within two hours of instruction, to maintain the frequency and voltage levels within acceptable limits and to provide at least three sequential black starts. The reactive capability to charge the transmission system is required according to different sites [18].

2.1.2.5 Frequency Response

The function of frequency response is similar to regulation. They are both trying to eliminate the mismatch between the generation and demand. The timescale of frequency response service will be much smaller, within 15 minutes. Moreover, providing this service will require a fast response rate, which is perfectly suitable for batteries and flywheels. Studies have revealed that the effectiveness of fast-response batteries and flywheels in frequency response could affect frequency control with about 40% less energy when compared to conventional generators because of their very fast response time [14].

2.1.3 Transmission Infrastructure Services

Transmission upgrade deferral can be realised by employing a small amount of energy storage when the peak loading exceeds the transmission rating capacity. It can defer the demand for an upgrade for a few years and extend the existing equipment lifetime. The peak loading occurs for only a few days per year. The key concern is making sure the energy storage capacity is enough for the peak demand. This saves upgrade investment and reduces the risk of underestimating or overestimating the load increase. In addition, energy storage systems can relieve the stress on transmission lines and avoid congestion-related costs and charges.

2.2 Battery Technology

It is crucial to evaluate energy storage systems technologies, since they possess different characteristics from conventional generations. Unlike traditional generations, energy storage systems operate in two-way power flow mode by charging and discharging. In addition, they are dispersed across both transmission system and distribution system to provide multiple services and do not have a specific energy source. All these characteristics make it more complicated to evaluate them.

Generally, evaluating a storage system involves evaluating the quantifiable value and monetizable value of the system [13]. The quantifiable value lies on grid impacts and incidental benefits of the storage system whose services have been identified based on current or potential system operating problems and the requirements of services to solve the problems. A multi-functional storage system supplies a core service together with any other compatible services so as to make the best use of the system capacity. The core service is usually of relatively high value and frequency response is chosen in this study because of its increasing market size for assets with a fast responding capacity and supplemental services are left for investigation in future studies. The monetizable value is distinguished from the quantifiable value by its focus on monetization for energy storage owners, while the quantifiable value represents the aggregated value across the whole system. They should both be taken into consideration when designing an energy storage system.

2.2.1 Evaluation Metrics

Before discussing different energy storage system technologies in detail, a brief introduction of the elements that make up the cost for the energy storage systems and five commonly used cost metrics are presented here for a better understanding of different technologies with respect to economy.

For an energy storage system, total plant cost is the sum of unit cost for power cost and energy cost. Power cost includes the cost of power conditioning system and auxiliaries costs and contributes to £/kW of the system cost. Energy cost determines the capacity of the system, which contributes to the £/kWh of the system cost. Moreover, running a battery storage system has additional operating costs, which include fixed Operation and Maintenance (O&M) costs, placement battery costs, variable O&M costs and costs to buy electricity from grid to charge batteries.

The Cost Metrics [14]:

In order to compare the effectiveness of the storage technologies, five cost metrics are commonly used taking debt and equity payments into account. They are introduced as follows.

Installed Cost (£/kW)

The installed cost includes the cost of all equipment for the battery storage and also the interconnection and enclosure. However, it assumes the site is available thus land costs and planning costs are not taken into account. It is also an input to calculate present value.

Levelised Cost of Capacity (£/kW-year)

The levelized cost of capacity is the revenue of discharge capacity needed to cover all life-cycle fixed and variable costs for the target return on equity for the project.

Levelised Cost of Energy (LCOE) (£/MWh)

The levelised cost of energy is the revenue for delivered energy needed to cover all life-cycle fixed and variable costs for the target return on equity for the project.

Present Value of Life-cycle Costs (£/kW Installed)

The present value of life-cycle costs does not only cover the operating costs but also takes the installed cost into account. Thus it is the sum of installed costs and all fixed and variable operating costs over useful life divided by the kW of installed discharge capacity.

Present Value of Life-cycle Costs (£/kWh Installed)

The present value of life-cycle costs is the sum of installed cost and all fixed and variable operating costs over useful life divided by the kWh of installed storage capacity.

Present value has broad applications in economics, also known as present discounted value. That is to say, the same amount of money today is worth more now than in the future. This is because it can be used for other activities and earn more money to make it more valuable in the future. The investment for battery storage systems is relatively high and their lifetime is relatively short compared to conventional storage systems such as pumped hydro and

Compressed air energy storage (CAES). Thus the present value of life-cycle cost is usually chosen to evaluate the cost-effectiveness of a battery storage system.

The formula to calculate present value PV is shown below:

$$PV = \frac{C}{(1+i)^n} \quad (1)$$

Where C is the future amount of money that must be discounted, n is the number of periods, i is the interest rate for one compounding period.

The applications for which different energy storage systems are suitable are shown in Fig. 5. As illustrated in [14], pumped hydro storage and compressed air energy storage (CAES) are suitable for supplying bulk storage in the grid because of their large sizes, being able to discharge hours to days. They are the only two commercial bulk energy storage systems available. In contrast, small size storage systems like batteries are able to discharge from seconds to up to hours.

Nevertheless, flywheels and superconducting magnetic energy storage (SMES) are also capable of supplying frequency regulation. In this report, the focus is on employing batteries. There are two main types of battery technology being considered to provide BESSs, these will now be discussed in Section 2.2.2.

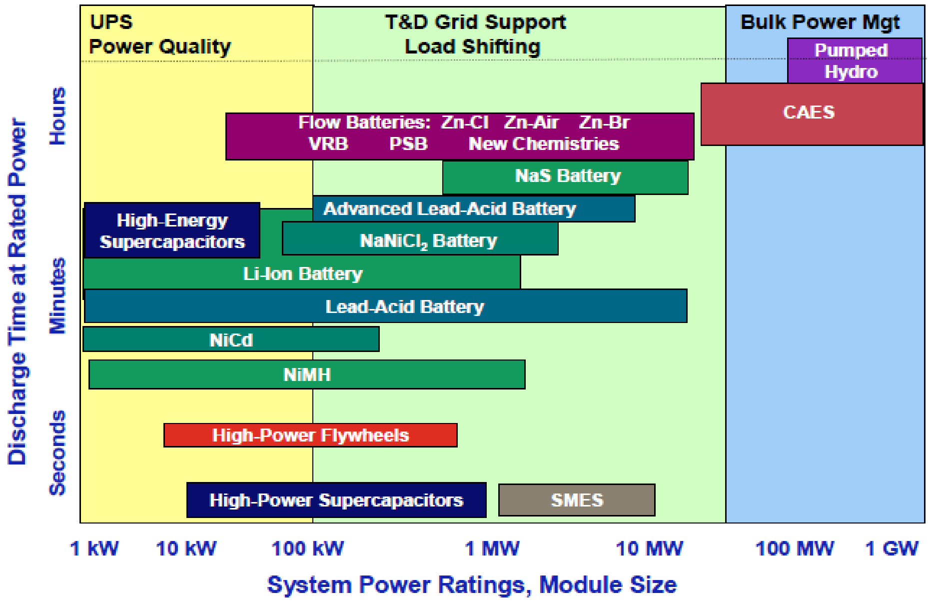


Fig. 5 Positioning of energy storage technologies [13]

2.2.2 Technologies to Supply Frequency Response

2.2.2.1 Lead-Acid Battery

Lead-acid batteries represent a mature and commercial rechargeable battery technology which has been employed for over one hundred years. The operating principle of the Lead-acid battery is to use lead-dioxide as an anode and spongy lead as cathode, immersed in diluted sulfuric acid electrolyte. When the battery is discharging, both cathode and anode become lead sulfate and electrolyte becomes water. While in the charging state, the positive electrode returns to lead-dioxide and negative electrode returns to lead. They are commonly used for automotive, marine and Uninterrupted Power Supply (UPS) systems. However, conventional lead-acid batteries have relatively lower power and energy density resulting from the high molecular weight of lead and shorter life cycle delivering 300 to 500 deep-discharge cycles. In order to improve their performances, two approaches are employed either by incorporation of carbon in electrodes or by means of advanced technologies, such as carbon-doped cathodes, granular silica electrolyte retention systems, high-density positive active material, and silica-based electrolytes. Nowadays, advanced lead-acid systems have been employed for wind and photovoltaic (PV) facility stabilisation and transmission and distribution applications and can stand more than 1600 deep-discharge cycles before degrading to a capacity of 80% (the standard measure of end-of-life) [14]. The efficiency of a 1MW/0.5MWh advanced lead-acid battery system for frequency regulation can reach 90% with a total cost of 2022 £/KWh [14].

2.2.2.2 Li-ion Battery

Rechargeable Li-ion batteries are already commonly used for electronic applications, such as mobile phones, laptops, cameras and portable devices thanks to their high power and energy densities, no memory effect and low self-discharge. Li-ion batteries can stand at least 500 cycles before fading to 80% capacity according to the data up to date [19]. There are many Li-ion chemistries, which give different performances. Among lithium cobalt oxide (LCO), LCO-lithium nickel manganese cobalt oxide composite (LCO-NMC) battery technologies, lithium iron phosphate has been shown to have much longer cycle lives with more than 90% remaining of initial capacity after 1000 cycles [20]. Lithium iron phosphate is a promising technology and is developing rapidly. According to the A123 System report [19], employing Nanophosphate in batteries can deliver more than 7000 cycles at 100% depth-of-discharge (DOD) with little impedance growth or power loss. Normally, since lithium batteries require constant charging current, a battery management system is needed for overvoltage, undervoltage, overtemperature, and overcurrent protection to ensure safe operation [9] [20], because the internal impedance will cause the heat-generating reaction. Nanophosphate is more chemically stable, with only a small amount of heat being subject to abusive conditions [19].

Nowadays, Li-ion battery system applications in utility grid-support applications, such as frequency regulation and renewable energy generation smoothing, are underway because of their attractive life cycle and high efficiency of up to 92%. A 12-MW frequency regulation and spinning reserve project employing A123 Systems' Li-ion Hybrid-APUs has been operated at AES Gener's Los Andes substation in Chile. The total cost of a Li-ion battery system with a 3MW/3MWh capacity for frequency regulation and renewable integration is currently 1062 £/KWh, which makes it economically feasible to use Li-ion battery technology [14].

2.3 Balancing services

As concluded in [14], supplying frequency regulation is one of the most promising applications for BESSs. In this section, current balancing mechanism in the UK is introduced. The UK high-voltage transmission network is under the control of National Grid Electricity Transmission plc (NGET) in England and Wales, Scottish Power Transmission Limited (SPT) in south and central Scotland and Scottish Hydro Electric Transmission Ltd (SHETL) in north Scotland. Among them, National Grid acts as a Transmission System Operator (TSO) taking the responsibility to ensure that transmission system is balanced moment by moment nationwide, hence maintain the system frequency within the normal operational limits. There are a few balancing services through which the National Grid achieve this goal. In the UK, statutory limit and operating limit are defined as 49.5Hz-50.5Hz and 49.8Hz-50.2Hz respectively. The current UK system active power balancing mechanism is accomplished by mandatory frequency response, firm frequency response, frequency control by demand management and newly added enhanced frequency response.

2.3.1 Mandatory Frequency Response

Mandatory frequency response is a condition of connection for generators to the GB Transmission System defined in the Grid Code published in 2017 [21]. All large power stations connected to the transmission network are obligated to supply this service. The definition of large power plants differs from site to site. Normally a power plant with more than 100MW capacity is regarded as a large power plant. While in Scotland, a power plant with more than 30MW will be treated as a large power plant and is obligated to supply mandatory frequency response [22]. Generators providing mandatory frequency response should adjust their active power output automatically to follow the load change.

National Grid as the System Operator (SO) procures the mandatory frequency response by three types of response services: primary response and secondary response for low frequency events and high frequency response reacting to the high frequency events. When the frequency drops below 49.8Hz, the primary frequency response requires generators to increase their outputs within 10 seconds after the event and they should be able to sustain the output for further 20 seconds. While secondary frequency response requires generators to pick up more demand within 30 seconds and they should have the ability to sustain the supply for further 30 minutes. When system frequency exceeds 50.2Hz, high frequency response requires generators to decrease their output within 10 seconds and keep deloading until instructed by the system operator.

2.3.2 Firm Frequency Response

Firm Frequency Response (FFR) allows non-BMU to participate in the balancing market through tender to complement the mandatory frequency response [23].

2.3.3 Frequency Control by Demand Management

Active power balance can also be achieved by reducing the demand. Frequency Control by Demand Management (FCDM) providers should be prepared to supply at least 3 MW capacity. Demand-side customers, who have committed to supplying this service should be able to cut off their demand within 2 seconds and can be interrupted for a total duration of 30 minutes [24].

2.3.4 Enhanced Frequency Response

Enhanced Frequency Response (EFR) was recently proposed and National Grid has successfully procured 200MW of enhanced frequency response through tender in July 2016. Significant changes of the power system mix so far have led to substantial increases in renewable generation, especially higher penetration of wind power, substantial decreases in conventional generation and increased allowance infeed loss from 1200MW to 1800MW since 2014. All these changes exert high pressure on the frequency response service. Frequency management can either be achieved by wind turbines or other decoupled generators providing synthetic inertia or procuring a faster frequency response where the full frequency response can be delivered within 1 second like enhanced frequency response. However, the latter method that wind farms provide synthetic inertia by storing kinetic pre-fault means that wind farms would have to curtail their generation for safety and suffer from the risk of further power reductions during the recovery period when frequency drops. EFR, according to [25] at the time of writing, requires the assets to respond to 100% active power output within 1 second and maintain the supply for a minimum of 15 minutes if required before slower responses coming up as shown in Fig. 6. It should be noticed that the time delay of 1 second includes detection of a frequency event, instructing a response plus delivering the reference output.

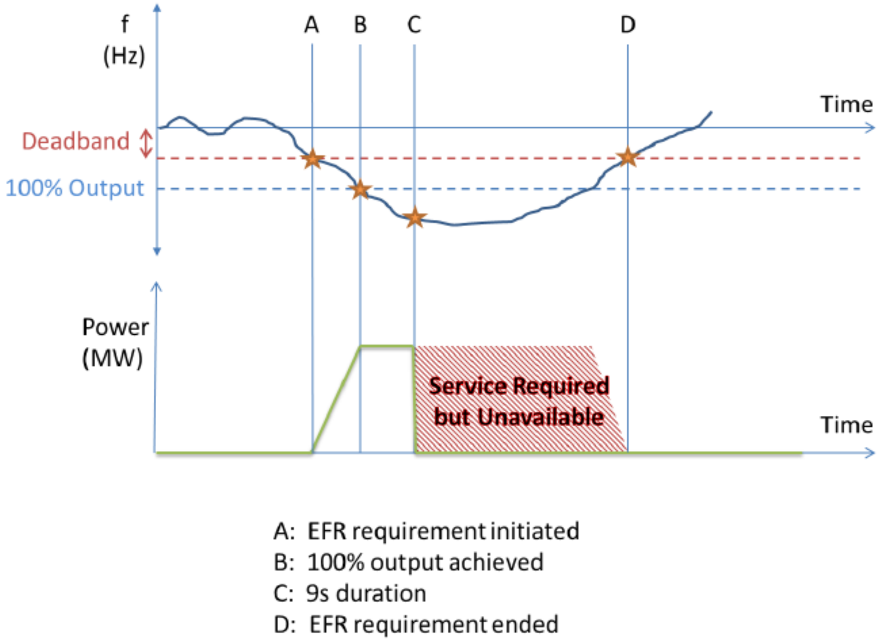


Fig. 6 Timescale to deliver enhanced frequency response [25].

There are two services of the enhanced frequency response, service 1 and service 2. They specify different requirements for providing enhanced frequency response as described in Fig. 7, Table 2 and 3. The assets should deliver continuous active power within the envelopes. Within the envelopes, storage assets have the flexibility to manage their state of charges for the further provision of the service, subject to the limitations on ramp rates as described in Fig. 8 and Table 4. As shown in Fig. 8 and Table 4, the ramp rate requirements are determined by the frequency, charge of frequency and the output of assets. During the service periods, meeting the service envelope is prior to providing the ramp rate limits. In the end, Service Performance Measure (SPM) would be calculated to evaluate the services and define the final service payments [25].

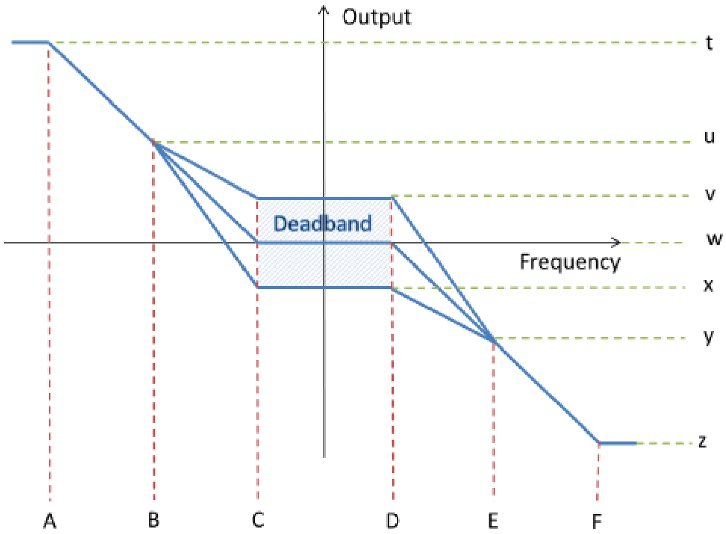


Fig. 7 Service envelops for delivering EFR [26].

Table 2 Service frequency envelops for delivering EFR [27]

Reference point	Service 1 (Hz)	Service 2 (Hz)
A	49.5	49.5
B	49.75	49.75
C	49.95	49.985
D	50.05	50.015
E	50.25	50.25
F	50.5	50.5

Table 3 Service capacity envelops for delivering EFR [28]

Reference point	Service 1 (%Capacity)	Service 2 (%Capacity)
t	100%	100%
u	44.44444%	48.46361%
v	9%	9%
w	0%	0%
x	-9%	-9%
y	-44.44444%	-48.45361%
z	-100%	-100%

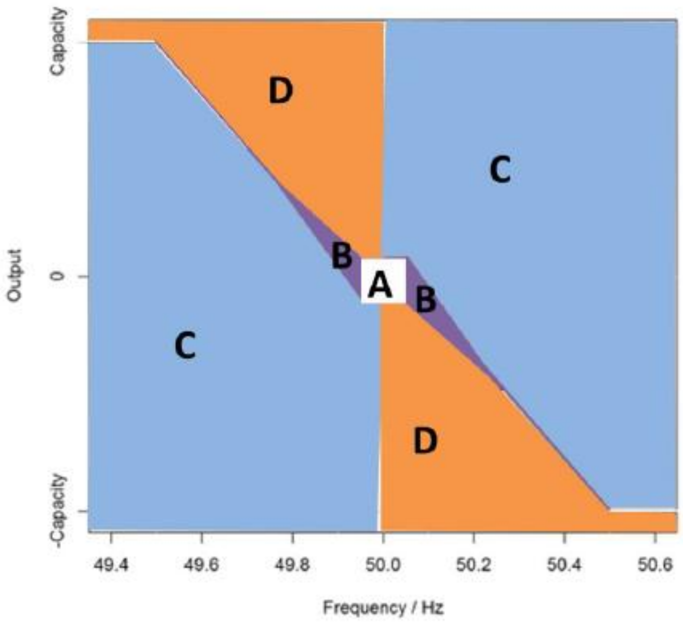


Fig. 8 Ramp rate requirements for delivering EFR [29].

Table 4 Ramp rate requirements for delivering EFR [20]

Area	Maximum Ramp Rate as a percentage of Operational Capacity (MW/s)	Minimum Ramp Rate as a percentage of Operational Capacity (MW/s)
A	1%	0%
B (service 1)	$\left(-\frac{1}{0.45}\left(\frac{df}{dt}\right)+0.01\right)*100$	$\left(-\frac{1}{0.45}\left(\frac{df}{dt}\right)-0.01\right)*100$
B (service 2)	$\left(-\frac{1}{0.485}\left(\frac{df}{dt}\right)+0.01\right)*100$	$\left(-\frac{1}{0.485}\left(\frac{df}{dt}\right)-0.01\right)*100$
C	200%	0%
D	10%	0%

2.4 Chosen Methodology Scheme

Through the literature review above, it is obvious introducing BESS in to the system is very significant as RES penetrations grow. While the high investment cost make it essential to find the optimal location and sizing of BESS. Dynamic performance is an important factor that decides how much benefit energy storage owners can get by providing frequency regulation services. This study proposed a dynamic system model with BESS introduced. Firstly, the dynamic behavior of conventional generators that participates in frequency response was studied. Then a multi-machine system model was built. The dynamic model was validated via National Grid published historical generation data, load data and shown to exhibits the correct dynamic behavior observed in the actual data sets. Then the performance of the BESS providing frequency response could be investigated. A dynamic model of the BESS was developed and the control strategy was decided so that the BESS could cooperate with conventional generators. In this study, Enhanced Frequency Response is the service that the BESS owners bid for to achieve income. Annual Annuity Evaluation was chosen to evaluate the economic behavior of BESSs.

CHAPTER 3: FREQUENCY REGULATION

3.1 Power System Stability Analysis

System frequency and voltages of each bus are the significant variables for the stability analysis of a power system. System frequency is mainly determined by the active power balance and voltages are mainly decided by the reactive power control. Since active power and reactive power are relatively independent of each other [3]. This section will focus on the active power control i.e. frequency control of the system is investigated independently and assumptions are made that voltages at each busbar are balanced. In real life, the accuracy of estimation of the system frequency is of significant to ensure the system operator make proper actions for a disturbance. Reference [26] presents an iterative technique for measuring the power system frequency.

System frequency evolution after a contingency is shown in Fig. 9. The shape of frequency deviation is decided by the power loss, system inertia and frequency response of the generating units.

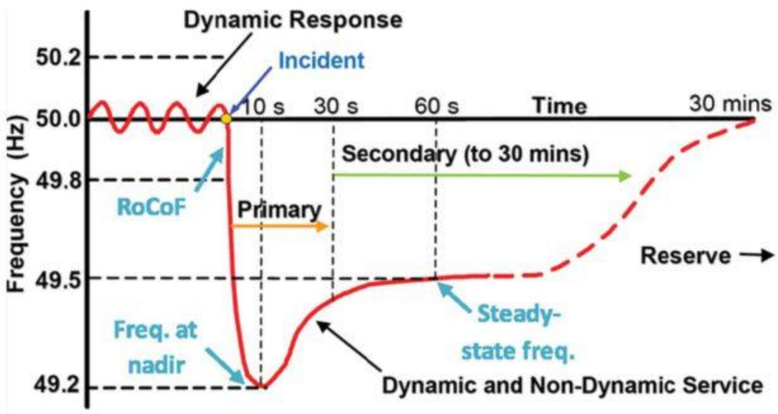


Fig. 9 System frequency evolution after a contingency (National Grid) [27].

3.1.1 System Inertia

The system inertia results from the energy stored in the rotating mass of the synchronous machine [3]. For a single synchronous generator, its mechanical torque equals the electrical torque in the steady-state [28]. The rotor motion equation is given by:

$$J\frac{d^2\theta_m}{dt^2} = Ta = Tm - Te \tag{2}$$

Where:

J is the total moment of inertia of the rotor mass $(\mathrm{kg \cdot m^2})$

θm is the angular position of the rotor with respect to a stationary axis (rad)

t is time in seconds (s)

Tm is the mechanical torque supplied by the prime mover (Nm)

Te is the electrical torque output of the alternator (Nm)

Ta is the net accelerating torque (Nm)

When the load of generator increases, the mechanical torque is larger than the electrical torque. As a result, accelerating torque Ta is no longer zero and the generator would accelerate to generate more power to pick up the increased load. Moreover, it is preferable to convert the mechanical and electrical torque expressions to mechanical and electrical power expressions by using (2) to get inertia constant:

$$P = \omega_r \cdot T \tag{3}$$

Because the angular velocity is given by:

$$\omega_m = \frac{d\theta_m}{dt} \tag{4}$$

Multiplying both sides of (2) by ω_m gives (5)

$$J\omega_m \frac{d^2\theta_m}{dt^2} = Pa = Pm - Pe \tag{5}$$

Since Pm, Pe and Pa are given in MW, dividing them by the MVA rating S_{rated} gives equation (6) in per unit form:

$$\frac{J\omega_m}{S_{rated}} \frac{d^2\theta_m}{dt^2} = P_{a(pu)} = P_{m(pu)} - P_{e(pu)} \tag{6}$$

$$2H \frac{S_{rated}}{\omega_{s^2}} \omega_m \frac{d^2\theta_m}{dt^2} = P_{a(pu)} = P_{m(pu)} - P_{e(pu)} \tag{7}$$

Equation (7) is also known as swing equation. Then the inertia constant is defined as (8) and its value normally lies between 1 and 10 seconds dependent on the type and the size of generator.

$$H = \frac{stored\ kinetic\ energy\ at\ synchronous\ speed}{generator\ voltampere\ rating} = \frac{\frac{1}{2}J\omega^2}{S_{rated}} \tag{8}$$

For a power system with multiple generators, the system inertia can be calculated from the initial Rate of Change of Frequency (RoCoF) in the first second following a large generation loss or demand increase by using (9), which indicates the robustness and capacity of spinning reserve of the system [29]. System frequency is determined exclusively by the inertial response in the first second after an outage [30].

$$H_{sys} = \frac{\Delta P}{2 \times (\frac{df}{dt})} \times f_0 \tag{9}$$

For example, in order to maintain the system stability under the largest allowed infrequent loss of 1800 MW and to meet the maximum RoCoF 0.125 Hz/s requirement [31], the minimum system inertia can be calculated as:

$$\mathrm{H_{sys}} = 1800/(2 * 0.125) * 50 = 360\ \mathrm{GVA} * \mathrm{H} \tag{10}$$

For the convenience of the simulating load frequency response, the system inertia constant is used, which can also be derived from:

$$H = \frac{energy\ stored\ in\ the\ synchronous\ machines}{the\ sum\ of\ the\ rated\ apparent\ power\ of\ all\ generators}$$

$$= \frac{\sum_{i=1}^{n} HiSi}{\sum_{i=1}^{n} Si} \tag{11}$$

3.2 Power System Dynamic Model

This section introduces the dynamic modelling of different types of generators and a multi-machine dynamic model is presented. The parameters of each model were set based on the typical values from [3] and were adjusted to imitate the performance of real power system. Values of parameters used could be found in Appendix A.

3.2.1 Conventional Generator Frequency Response

As illustrated in [3], a load change will immediately cause the electrical torque to change and follows adjustments of the generator output to maintain the electrical power and mechanical power in balance. Moreover, for some of the loads that are not purely resistive, they would be affected and would change their value in response to a frequency change. In general, system load comes from a variety of electrical devices and could be categorized into non-frequency-sensitive load and frequency-sensitive load considering their contribution to the frequency change. The generator response and load response to frequency deviation is illustrated in Fig. 10 and expressed in equation (12). Typical values of load-damping constant D are between 1 and 2 percent [3]. As illustrated in equation (12), D represent the relationship between frequency deviation and load change. If D equals 2, it means that 1 percent change of frequency would cause a 2% change of the load.

$$\Delta P_e = \Delta P_L + D \cdot \Delta\omega_r \tag{12}$$

Where:

ΔP_L is non-frequency-sensitive load change (MW)

$D \cdot \Delta\omega$_r is frequency-sensitive load change (MW)

D is load-damping constant

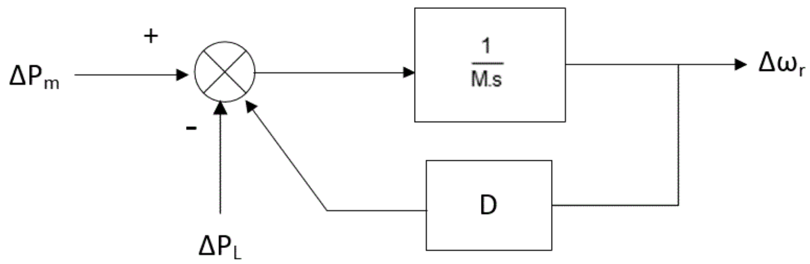


Fig. 10 Block diagram with inertia and load response

However, for a multi-generator system, frequency is a common factor throughout the system. All the generators in the system would be affected by frequency deviations. And the load sharing between generators is determined by their set droop characteristics as shown in Fig. 11. The droop R, or so called percent speed regulation, is defined as the ratio of speed deviation or frequency deviation to change in valve position or power output [3]. It could be expressed as:

$$Percent\ R = \frac{percent\ speed\ or\ frequency\ change}{percent\ power\ output\ change} \times 100$$

$$= \left(\frac{\omega_{NL} - \omega_{FL}}{\omega_0}\right) \times 100 \tag{13}$$

The measured speed compared with the reference speed, thus gives the error signal $\Delta\omega_r$. The error signal $\Delta\omega_r$ then is amplified and integrated to give a control signal ΔY to control the valve position of a steam turbine or hydraulic turbine [3]. While at the same time, it causes the steady state frequency deviation $\Delta\omega_{ss}$ as shown in Fig. 12, which would need supplementary control under instructions from the system operator or the actions of Automatic Generation Control (AGC) technology.

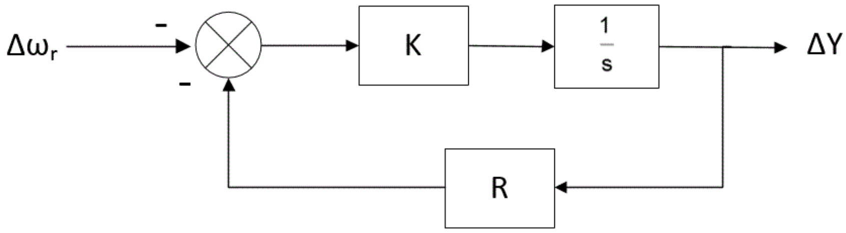


Fig. 11 Block diagram with droop characteristic feedback

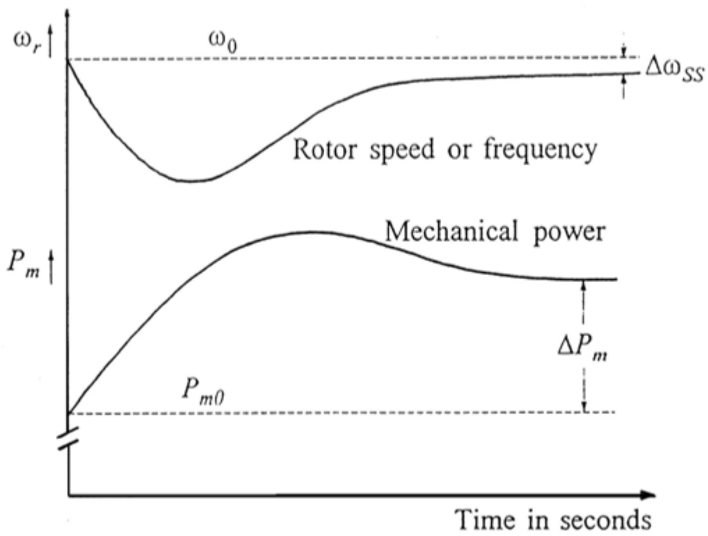


Fig. 12 Response of a generating unit with a governor having speed-droop characteristic [3]

3.2.2 Single Generator Model

This section describes the model of a single coal generator, gas generator, pumped hydro storage system and battery individually. The system model was implemented by using MATLAB/SIMULINK. The three most representative generation types, coal generating units, gas generation and pumped hydro are included in the new power system frequency response model. The base power was set as the total capacity of the system.

According to Digest of UK Energy Statistics-2015, in the UK system, nuclear power contributes to 29.7% of electricity production followed by gas generation and coal generation, accounting for 29.5% and 22.3% of total electricity production respectively [32]. Since nuclear power does not usually participate in frequency response, because of security concerns to maintain its output steady in the longer period, nuclear power is not discussed here. Pumped hydro storage system was introduced because of its wide usage in supplying frequency response services.

3.2.2.1 Gas Power Plant Model

A number of research works have presented comprehensive studies of gas turbine modelling, describing dynamic behavior at different levels of detail [33]. First the theory of the operation of gas turbines is presented briefly, and a detailed description of the gas turbine model used in this research is given.

Gas turbines consist of an axial compressor, a combustion chamber, and a turbine [34]. The construction of gas turbines is shown in Fig. 13. In the process of stages 1 to 2, air is compressed through the axial compressor and then mixed with fuel in the combustion chamber. The pressure in the combustion chamber is maintained constant, while the temperature is increasing, the hot air drives the turbine to rotate. The maximum gas turbine power output is related to the ambient air temperature and turbine rotating speed. The steady-state rated output of gas turbines depends on the combustion ambient inlet temperature and the turbine rotating speed. Reference [35] explains the physical reason behind these relationships.

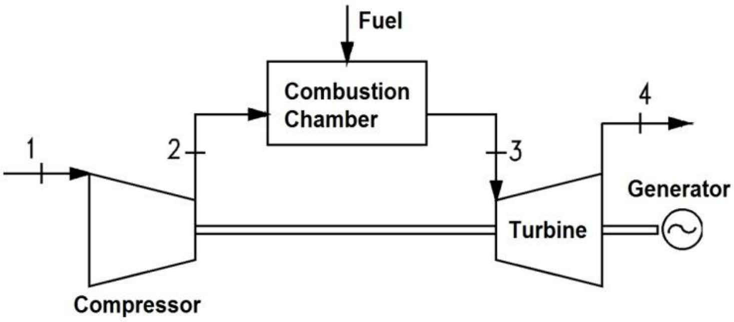


Fig. 13 Gas turbine construction [36].

The gas generator model developed in this research is shown in Fig. 14. Since most gas power plants are using Combined Cycle Gas Turbine (CCGT), this model is built based on a CCGT model. The gas model takes the turbine rotating speed and ambient temperature into account and sets limitations for both of these respectively. The input signal is still a combination of the frequency of gas turbines supporting the area and the frequency of the whole system. A reference power is set according to the percentage of electricity from gas power plants to the whole system electricity generation. A fuel system time constant is employed to express the process of adding fuel to the combustion chamber and a set of turbine time constants are employed to present the process between the turbine and changes in its rotating speed. The power output of the gas turbine is calculated and thus the frequency response from the gas power plants was simulated. The parameters in Fig. 14 are set based on those given in reference [34].

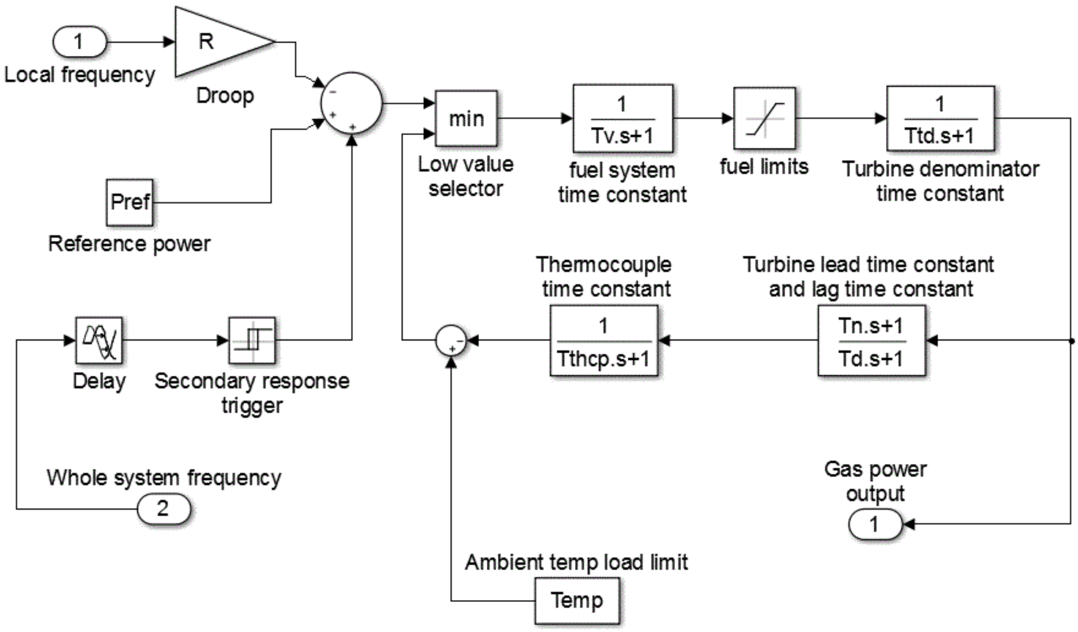


Fig. 14 Block diagram of frequency response of gas power plants

3.2.2.2 Coal Power Plant Model

The control system of the steam generator representing a large coal power plant as the main generation in an area is shown in Fig. 15. The steam generator should be responsive to both frequency deviations caused by the local area load change and the instructions from the system operator to balance the generation and demand mismatch in the whole system. The power imbalances from a local area and somewhere else in the rest of system would make the governor change its valve position and thus increase or decrease the fuel infeed to speed up or slow down the turbine.

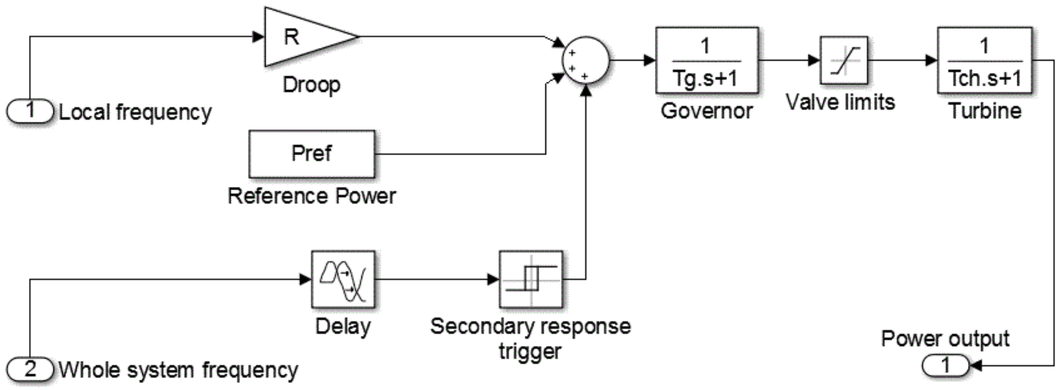


Fig. 15 Block diagram of frequency response of coal power plants

The frequency error signal Δf comes from the local frequency deviation and the whole system frequency deviation. This signal together with the reference power output are sent to the governor, where the valve change signal is generated and drives the turbine to speed up or slow down. A valve limitation is set to reflect the maximum power output available from the steam generator. Tch is the time constant of the steam turbine to present the speed adjustment process. The parameter settings are chosen according to [37].

3.2.2.3 Pumped Hydro System Model

In real life, large generation losses or unexpected sudden demand increase are possible. The frequency signal of the whole system is under the supervision of the control center and generation instructions made by the system operator would be sent to assets participating in the frequency response services to make adjustments to their generation output. It was assumed that pumped storage systems take up the majority capacity of the secondary frequency response in this research. Thus, a simple secondary frequency response model is presented in Fig. 16. A low frequency trigger and a high frequency trigger send alerts to the control center when the system frequency is lower than 49.8Hz or higher than 50.2Hz. The frequency response selector block send the preset output to turbines to further eliminate the difference between generation and demand. A generic time constant is employed here to present the behavior of turbines [3]. The power output of the pumped hydro storage system is regarded as the secondary frequency response of the system to bring the frequency back to normal operating points.

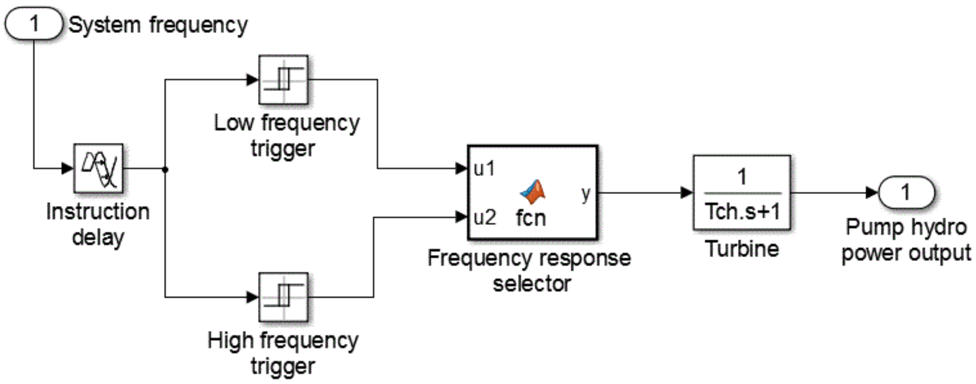


Fig. 16 Block diagram of frequency response of pumped hydro storage system

3.2.3 Multi-Machines system frequency response

The multi-machine system model used in this research consists of a steam generator, a gas generator and a pumped hydro storage system as shown in Fig. 17. The steam generator represents a set of coal power plants in an area. The gas power plants are located in another area. The pumped hydro storage system is used to reflect the secondary frequency response of the system. The coal generation and gas generation change their power outputs to balance the generation and demand of their supporting area and keep the whole system in balance. It is assumed that the amount of load they take up is in coincident with their generation at the moment when any frequency deviations occurs.

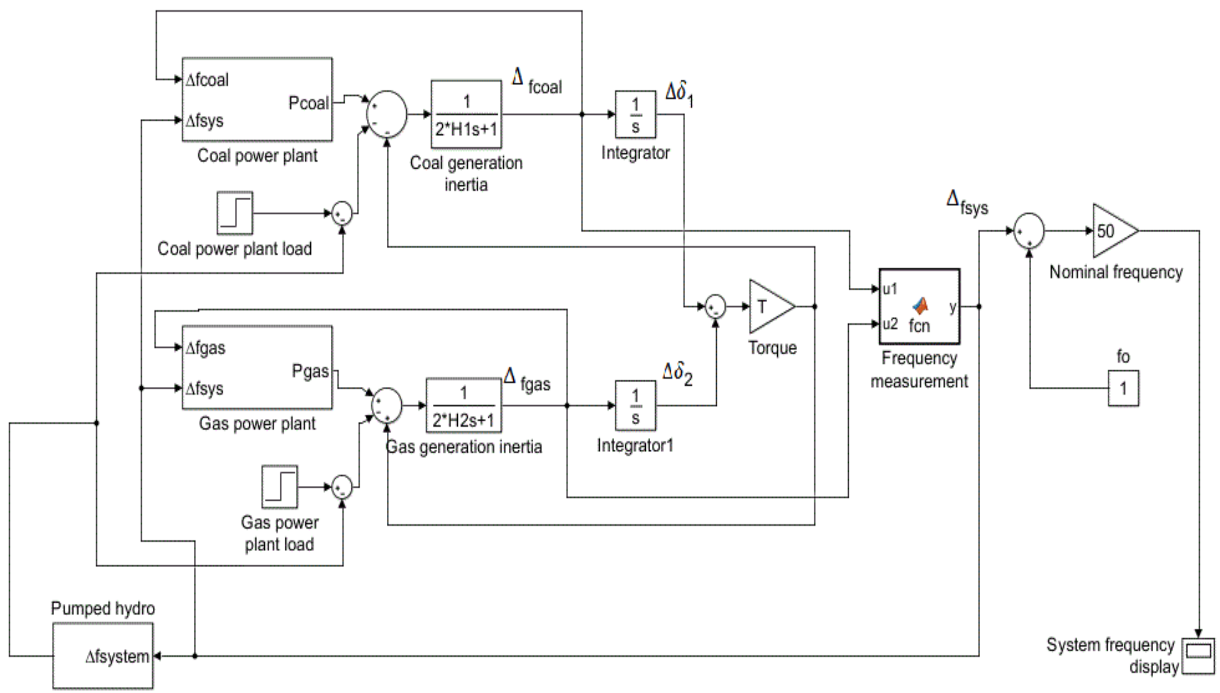


Fig. 17 Block diagram of frequency response of a multi-machines system

3.2.4 Results and Validation of Multi-machines System

To validate the model, the frequency response of a large frequency event which happened on 2nd March 2012, is simulated. The generation mix is shown in Table 5. Nuclear power was regarded as a negative base load, since it is not very practical to change the output of nuclear power other than over scheduling periods. Wind generation is also treated as a negative load, because it is supposed that wind was not participating in frequency response. However, it can be foreseen that wind power would contribute to most of the fluctuations of generation and some wind farms would supply synthetic inertia in the near future.

Table 5 Generation mix data on 2nd March 2012

Generation	**MW**	**MVA**	**MVA*H**	**H**	**Ht**
Nuclear	10748.4	16850	65991	3.92	4.31
Gas	8673.43	14283	89745	6.28	
Coal	21287.12	26911	102981	3.83	
Hydro	583.03	853	2814	3.30	
Wind	1746.908	1745	0	0.00	
Pumped Storage	477.63	786	2889	3.67	
CHP	228.02	507	2501	4.94	
Total	43744.538	61935	266922		

Fig. 18 shows the results of simulated frequency response of a multi-machines system model. According to the event a 1200MW generation loss is applied to the model at 10 s. The system frequency reaches its lowest value, nadir frequency, at 49.65Hz about 15 s after the generation loss. It can be observed that the frequency did not change smoothly. Instead, it oscillated until reaching its new steady-state at 49.8Hz about 1 minute later. A steady-state error remained and it could have been solved either by AGC or control from system operator. The actual frequency curve for the 2nd March event is shown in Fig. 19 [38]. It can be seen from Fig. 19

that the frequency dropped at 20:14:06 and reached it lowest value after about 5 seconds. Due to frequency response from generators, the frequency went up to around 49.7 and stay steady after 30 seconds. The studied time is marked in the red circle, which is in the scope of primary frequency response. Since the UK does not employ AGC, but instead, adjusts generation output via the system operator's instruction, we assume that the generation continues to go up to bring the frequency to the safe zone. In general, the variation curve of the simulated model is coincident with the actual frequency curve, which means that the system inertia and parameters of the simulated model appear to give realistic frequency response in this real life scenerio.

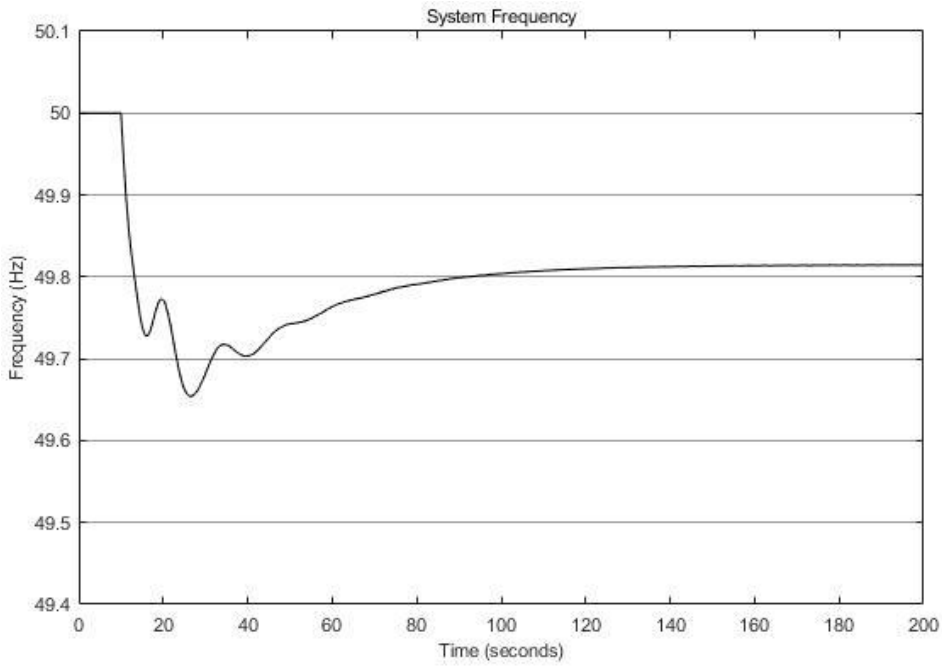


Fig. 18 Frequency response of multi-machines system

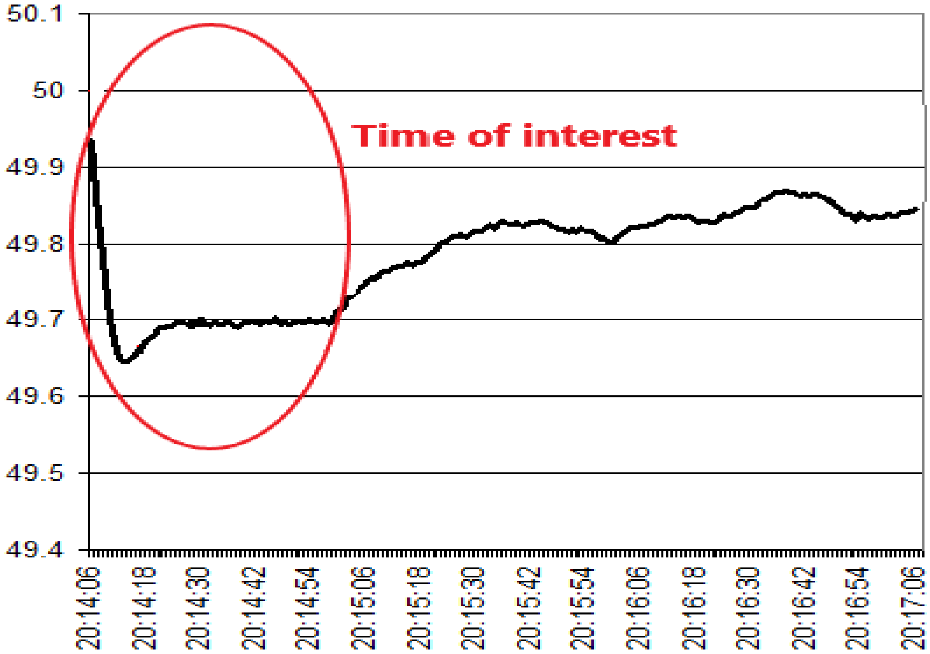


Fig. 19 Actual frequency curve for 2nd March event [38].

Fig. 20 shows the steam generator and gas generator angle changes in response to the generation loss respectively. During the event, they both dropped at first and then went up to new steady states. It can be seen that the coal generator dropped faster than the gas generator with more oscillating as well.

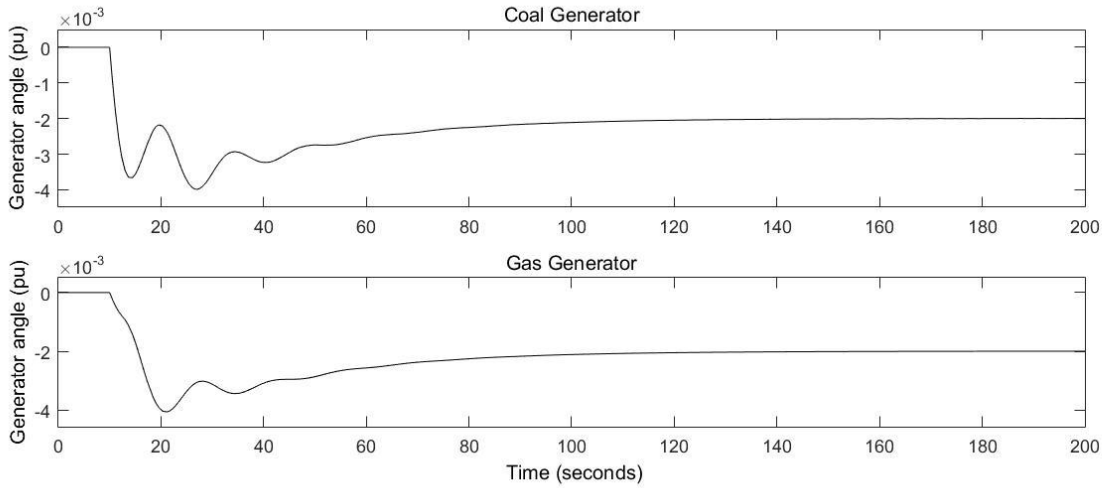


Fig. 20 Generator angles of generators

In Fig. 21, the generation outputs from coal generation and gas generation together with pumped hydro storage system are presented. In accordance with the expected results, both coal and gas power plants increase their power outputs. Both coal and gas generators reach their maximum output power within 5 s. Pumped hydro storage responded at around 16 s and increased its output slowly to 400MW taking around 20 s. After the pumped hydro came available after a while, coal generation decreased by 7% of its maximum output.

The behaviors of generators in response to the generation loss or load change show that different types of generators have different performances in supplying frequency response. Thus different balancing requirements come up among areas, further demonstrating that the locations of the BESSs in the transmission system is of significance. Also, the transmission losses exert an important impact on effectiveness of BESSs as well.

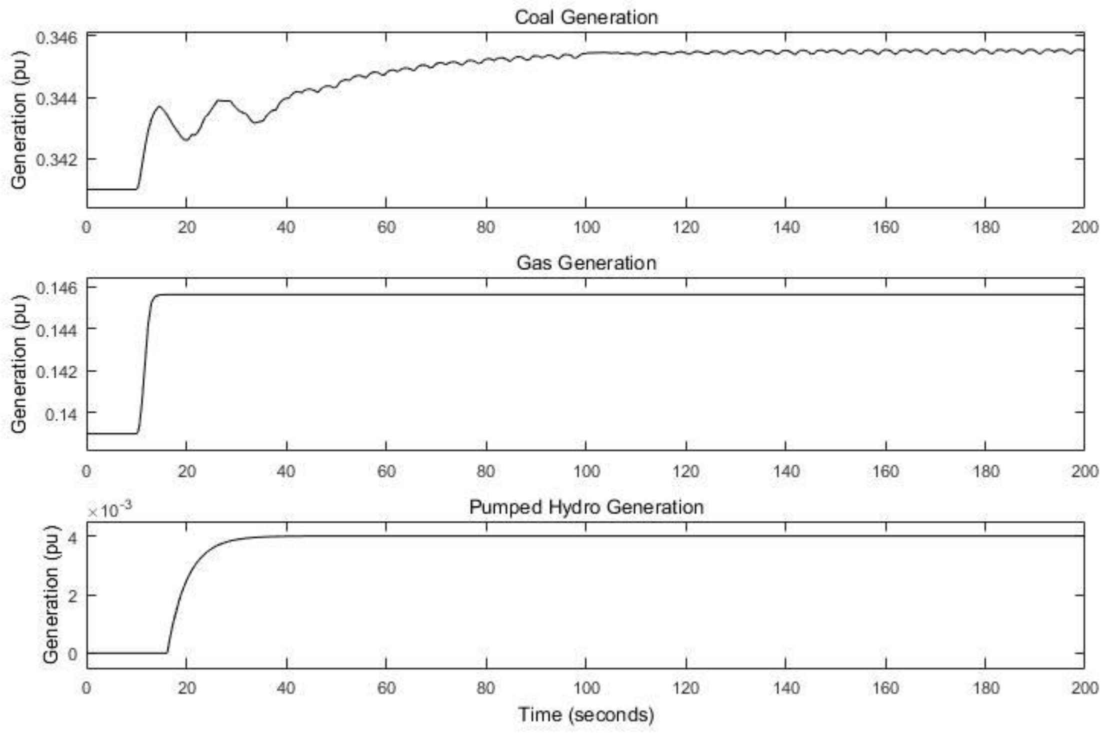


Fig. 21 Power outputs of generators

CHAPTER 4: ENERGY STORAGE SYSTEM

In order to investigate the performance of grid-scale BESSs to provide frequency response in different areas, the balancing requirement and dynamic model of the BESS is presented in this chapter.

4.1 Balancing Requirement for BESS

4.1.1 Balancing Power Estimation

The balancing power of the whole system is estimated in this section. Since BESSs are fast, responsive and efficient, the implementation of BESSs will have a significant impact on the frequency profile. To use the post-regulated historic frequency data is not realistic. Instead, historic wind outturn data and day ahead forecasting data were used to estimate balancing power [39]. The balancing power of the system is given as follows:

$$P_b = P_a^w - P_f^w \tag{14}$$

Where

P_b is the total balancing power (MW)

P_a^w is actual wind outturn (MW)

P_f^w is day-ahead wind forecast (MW)

In this study, we focus on eliminating the effect of inaccurate estimation under increasing amounts of wind penetration. It was assumed that the generation was aligned with the current planned UK generation. For conventional generators, we could generate scheduled output in most cases. However, for renewable energy sources, especially wind, the actual wind generation outturn was aligned to be the same as the day ahead forecast wind generation in most cases. Thus a high wind penetration leads to more unpredictable changes of generation. Furthermore, the demand forecasting errors and transmission losses were negligible compared to wind forecasting errors. Figure. 22 shows the total balancing power requirement with super-imposed wind forecasting errors on 1st Jan 2015 as an example. Fig. 23 shows the difference between actual wind out-turn and day-ahead forecast in 2015.

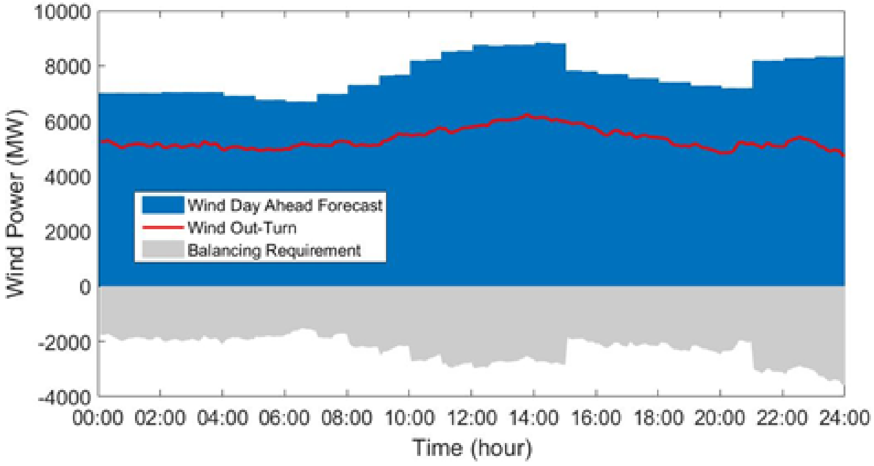


Fig. 22 Balancing power requirement imposed by wind forecasting errors on 1st Jan 2015.

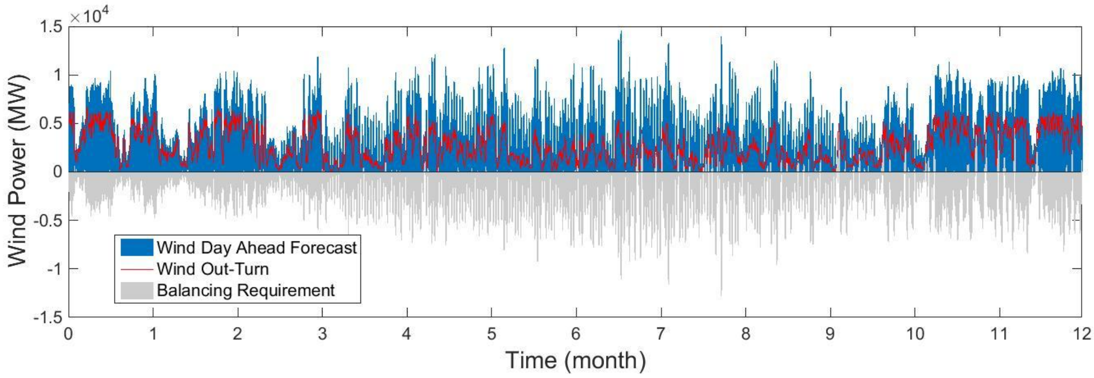


Fig. 23 Wind day ahead forecast and wind actual out-turn in 2015.

As shown in both Fig. 22 and Fig. 23, the wind out-turn is lower than its day-ahead forecast. Typically, the actual wind out-turn is lower than the day-ahead forecast value. In actual practice, wind curtailment is an intentional reduction by the System Operator to maintain the system stability. Also in some cases, wind power is curtailed due to the transmission constraints and system non-synchronous penetration (SNSP) [5]. According to [5], it could be noticed that the level of errors are larger when the wind power is at a high level. This is due to the imperfect of forecasting technology. Moreover, the recent increase in wind power is likely to be an additional contributor that imposes inaccuracy on the currently used forecasting model. Thus eliminating the effect of inaccurate estimation under high wind penetration is set as the target of operating BESSs.

4.1.2 Synthetic Generation/Load Profile

To simulate a full detailed UK system costs a huge amount of computer time, having high requirements for the computing devices to run the simulations. Thus a simplified system was be a better choice in this research. The generation/load data was synthesized based on the real generation mix data from GridWatch website, which is courtesy of Elexon and University of Sheffield [48].

A 12-bus UK equivalent system was implemented based on [40] [41] to produce a representative synthetic load profile of the UK system. This 12-bus power system model was originally built for validation of FACTS models. The platform allows detailed electromagnetic transients simulation for its manageable size [41].It has been proved that it is valuable for the validation of reduced order models like transient stability models, which meets the demand of this research. Moreover, this 12-bus system model does not impose heavy burden on the computing devices, and the simulations for each area over a year could be finished in less than one day.

The layout of the 12-bus system is given in Fig. 24. Area 1 is the biggest conventional generation area with industrial and residential loads. Area 2 is the dominant wind power generation area, including onshore and offshore wind generation with rural loads. Area 3 is a heavy load center with the most gas generation. The system is considered to have a similar load profile and power flows as the UK power system.

The 12-bus system was implemented in MATLAB/PSAT version 2.1.10 [49]. Generation and load profile data was produced based on real-time NGET generation mix data including nuclear, thermal generation, hydro generation and wind generation during 2015, which is recorded every 5 minutes. Thus, in the study, adjustment of generators' outputs was updated every 5 minutes and is given by:

$$\Delta P_{ss}^{i}(t) = P_{ss}^{i}(t+5) - P_{ss}^{i}(t) \tag{15}$$

Where:

ΔP_{ss}^{i} is the MW variation between steady-state generation levels in 5 minutes at bus i

P_{ss}^{i} is the MW generation of bus i generation

t is time in minute

It is assumed that the voltage control has been achieved by existing voltages regulation services. Thus voltage stability is not in the scope of this study.

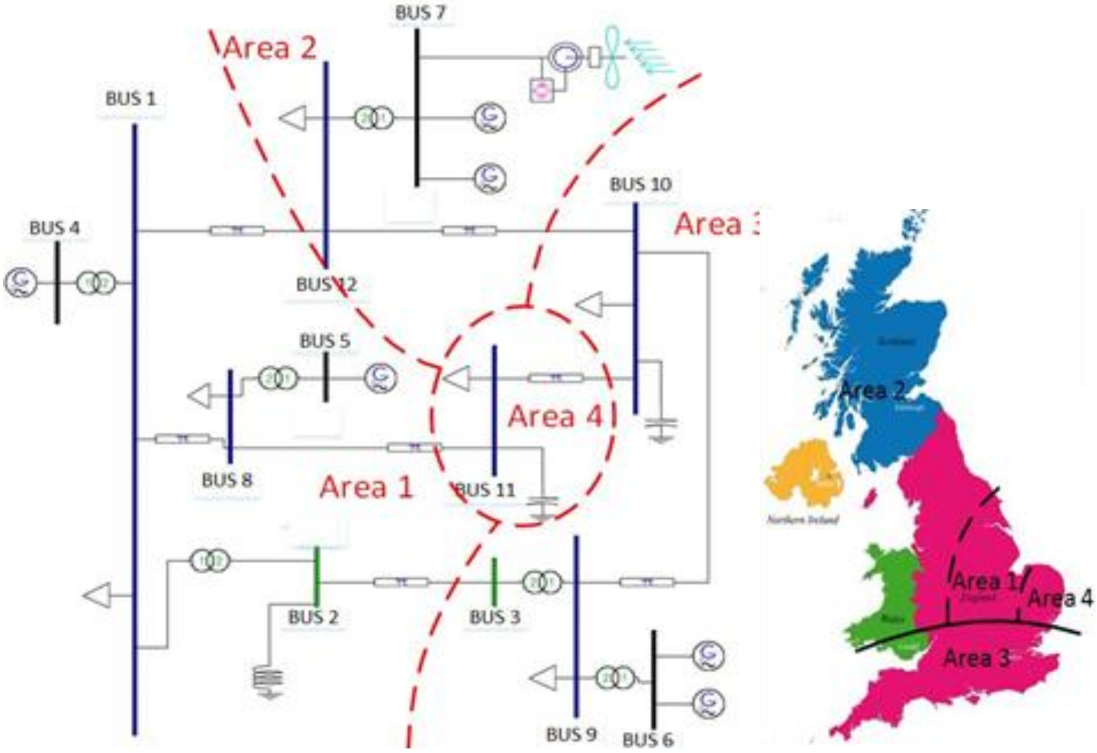


Fig. 24 Layout of 12-bus system in the UK [40].

4.2 BESS Dynamic System Modelling

4.2.1 Balancing Power Allocation and Extraction

Since BESSs are suitable for supplying fast ramp frequency response efficiently, the balancing power of each area is further decomposed by using a first order filter as illustrated in Fig. 25 [42]. This is able to decompose the signal into fast cycling components and slow cycling components, and then pass these signals to control the outputs of BESS and conventional generators respectively. The time constant of the first order filter was set at 1800 seconds so that the slow cycling components represent the smoothed balancing requirement changes every 30 minutes, which can imitate the respond time of conventional generators. The balancing requirements were decomposed into fast cycling components and slow cycling components are illustrated in Fig. 26 and can be express as:

$$P_b = P_{fast} + P_{slow} \tag{16}$$

Where:

P_b is the balancing requirement

P_{fast} is the fast cycling components

P_{slow} is the slow cycling components

In this study, BESSs responded to the fast components and slow cycling components were allocated to conventional generators.

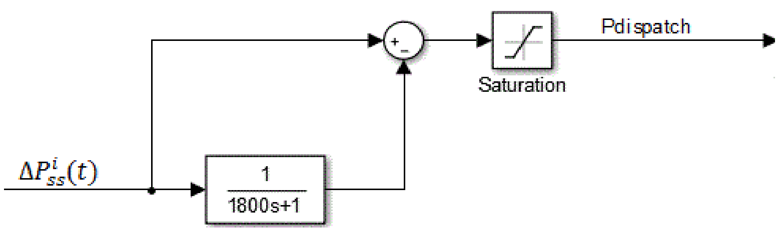


Fig. 25 Block diagram of balancing requirement decomposition.

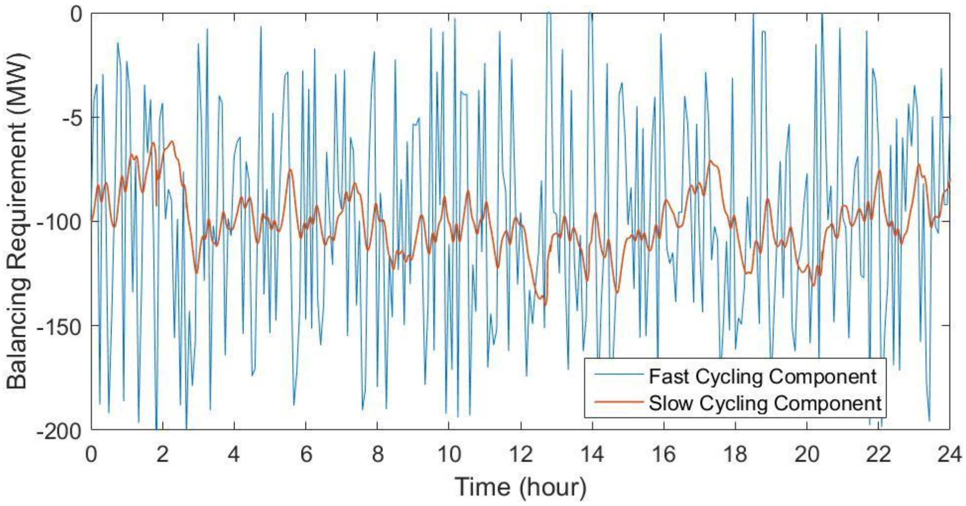


Fig. 26 Balancing requirements allocation.

Next, the multi-machines dynamic system model was implemented to demonstrate the effectiveness of BESSs with a capacity of 200MW/50MWh. Fig. 27 presents the simplified outline of the dynamic system with BESS installation in a generation area. Nuclear power generation supports the base load and it is assumed to be fairly constant compared to other generation types. System frequency deviation was computed based on balancing power and system inertia. In this study, the generic operation processes of the BESS that was applied is as follows [11]:

$$\begin{cases} P_{Battery} = P_{dispatch} - P_{offset} \\ Charging\colon E_{Bat} = \eta_{ch} \int P_{Battery} dt\,, P_{Battery} < 0 \\ Discharging\colon E_{bat=} \frac{1}{\eta_{dch}} \int P_{Battery} dt\,, P_{Battery} > 0 \end{cases} \quad (17)$$

The term $P_{Battery}$ is the total power output of a BESS, $P_{dispatch}$ is the output power to supply frequency regulation, P_{offset} is the offset power to maintain State of Charge (SOC) of the batteries, and E_{Bat} is the remaining capacity of a BESS. η_{ch} and η_{dch} are both set as 95% to represent the charging and discharging efficiency of batteries.

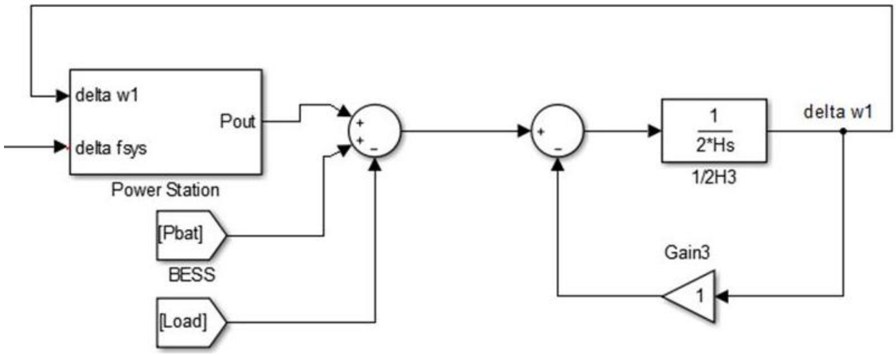


Fig. 27 Schematic block diagram of a generating area with BESS installed.

In this study, the offsetting process included a preparation period and an offsetting period based on the Regulation Energy Management (REM) method utilized by California ISO [43]. The operation and offsetting process of a BESS is shown in Fig. 28. The optimal operating SOC of the batteries is 50% according to [11]. The BESS operating around 50% SOC can reach its highest economic value over its whole lifetime [11]. Thus the preferred SOC for energy offset was set to 50% [11]. In this study, the BESS energy was offset every 30 minutes so that it could work on a continuous basis. The SOC of the batteries was maintained within the range of 20% to 80% to protect the batteries from over charging and over discharging. If the SOC of the batteries was below 20%, then the BESS would stop discharging and only accept charging instructions. On the other hand, if the SOC of the batteries was over 80%, then BESS would only accept discharging instructions.

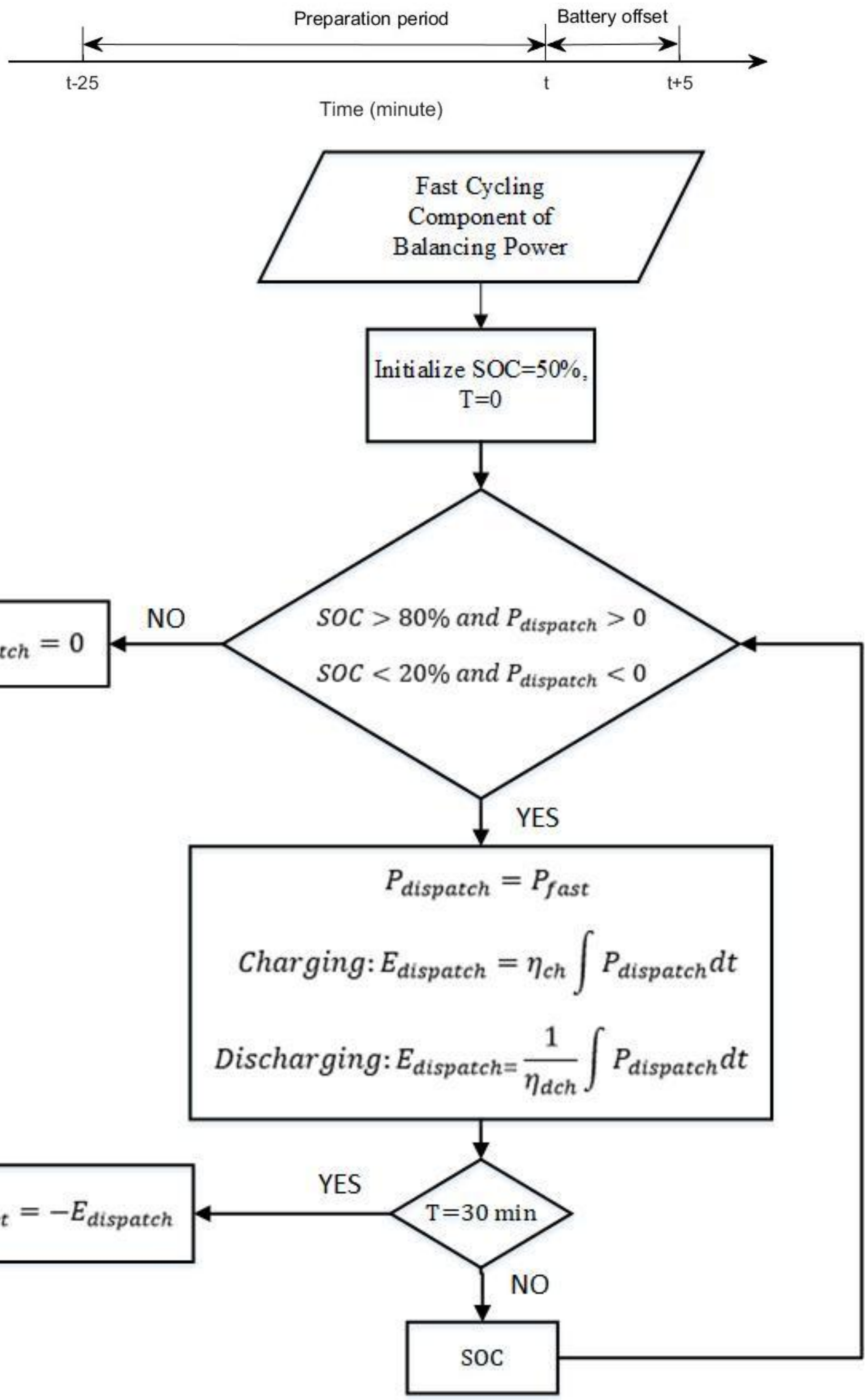


Fig. 28 Operation of BESSs for frequency regulation.

CHAPTER 5: RESULTS

5.1 Dynamic Simulation & Economic Analysis

5.1.1 Dynamic Simulation

The simulation used the model of a system shown in Section 3.2.4 that includes coal generation, gas generation and hydro generation in order to allow a detailed dynamic study. In this study, a grid-scale BESS can be placed in Area 1, Area 2 and Area 3.

Having achieved the representative dynamic model of the system, as described earlier, the data set of the actual generation mix recorded every 5 minutes throughout a year in 2015 was fed into the model to study the performance of the BESSs in providing frequency response. The generation mix data set is available from GridWatch and it is courtesy of Elexon portal and Sheffield University [44]. The simulated frequency curves determine the operation of the BESS which leads to different lifetime profits for each BESS located in different places as illustrated in Chapter 4.

System frequency simulation results obtained for the BESSs installed in Area 1, Area 2 and Area 3 for one day on 1st Jan 2015 is shown in Fig. 29 as an example. In Fig. 29, the upper graph shows the 24-hour system frequency deviation of the current power system on 1st Jan 2015 without BESS. The lower graphs show the simulated system frequency with the BESS located in Area 1, Area 2 and Area 3, respectively. It can be observed that with the BESS installation, system frequency was more tightly controlled when compared to the case without the help of the BESS. This is especially true when the BESS was installed in Area 1. A quantitative analysis of the results shows that the system frequency of the original system, without the BESS, had a standard deviation of 0.128Hz, which was greatly reduced to 0.075Hz after installing the BESS in Area 1. The standard deviation of system frequency in Area 2 and Area 3 dropped to 0.106Hz and 0.107Hz respectively as summarized in Table 6.

Fig. 29 demonstrates that the BESS could significantly improve the system frequency deviation either from the respective of standard deviation or deviation range, thus the number of unacceptable frequency deviation events decreases. By running the data set for a year, it was shown that the frequency was better improved by installing the BESS in Area 1, which is coincident with the result shown in Fig. 29. However, if the BESS was more frequently used by setting the time constant of the low pass filter in Fig 25 to a higher value, this leads to less lifetime profit, the benefit of having a BESS in the system decreases. Thus it is necessary to investigate the lifetime profit that can be achieved in each area, which is discussed in the following section.

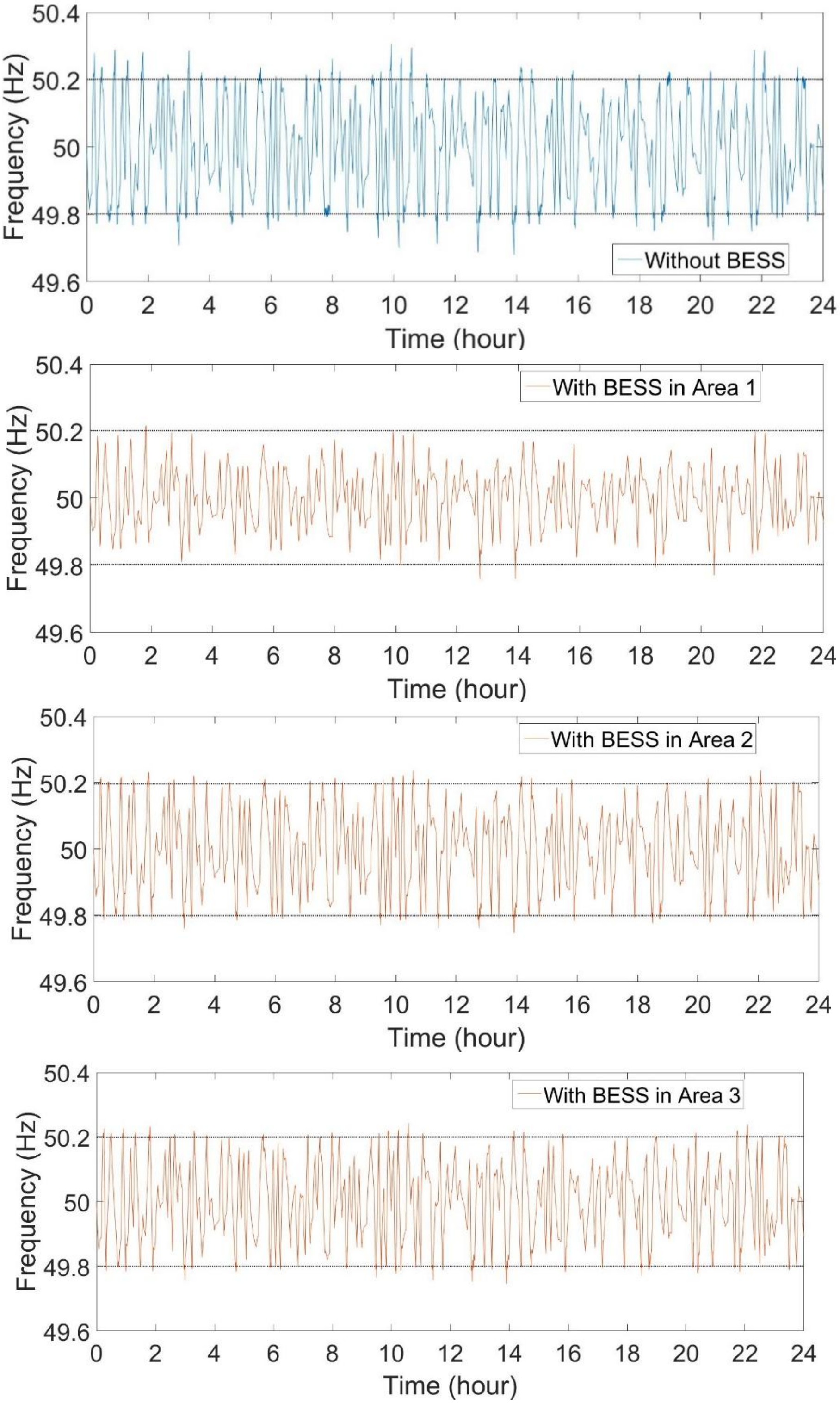


Fig. 29 Simulated system frequency for 1st January 2015.

Table 6 Dynamic performances comparison of BESS in different area

	Standard deviation	Min	Max
No BESS	0.128	49.69	50.31
BESS in Area 1	0.075	49.76	50.21
BESS in Area 2	0.106	49.76	50.23
BESS in Area 3	0.107	49.75	50.24

5.1.2 BESS Lifetime Estimation

To identify the lifetime profit, it is necessary to estimate the lifetime of batteries, since the investment cost of the BESS is higher and the lifetime of the BESS is shorter than conventional generators. Furthermore, a short lifespan BESS could lead to increased replacement costs. The lifetime of the BESS would have a direct impact on the economic value of the BESS. The degradation of batteries can be categorized into calendar-related degradation and cycle-related degradation. In general, the factors that affect the lifetime of a battery is temperature, depth of discharge, cut-off voltage/current and charging/discharging current, which makes it a complicated problem [7]. Thus the operation of batteries will affect the economic performances of BESS.

To evaluate economic effectiveness of BESSs more accurately and take account of battery round-trip losses, a lifetime estimation was carried out using the method known as “rain-flow counting” [45] [46]. Rain-flow counting algorithm was developed by Tatsuo Endo and M.Matsuishi in 1968 and it is widely used in fatigue life of a structure subject to complex loading analysis. This concept was used to estimate the cycle-to-failure of batteries in power system applicants in [45]. It has been proven that it is valuable for estimating the lifetime of batteries as well.

LiFePO4 battery technology was used in this study, because of its high energy/power capacity and its wide operation range. It was assumed that the ambient air temperature is 25 ℃. The degradation of batteries is related to depth of discharge, d, and calendar usage as given by:

$$Lifetime(days) = \frac{N_{days}}{W}$$

$$W = \sum_{i=i_{min}}^{i=i_{max}} \frac{N_{di}}{C_{di}} \tag{18}$$

Where:

N_{days} is the number of test days, which was chosen as 365 days in this study

W is the total battery life fraction consumed estimated for different cycle ranges i

N_i is number of cycles at depth of discharge d

C_{di} is cycles-to-failure at depth of discharge d.

Rain-Flow counting results for the number of cycles at each depth of discharge, was computed for a year and are presented in Fig. 30. In Fig. 30, it can be seen that the average operating SOC of batteries in Area 1 was around 49% to 51%. Average SOC of batteries in Area 2 was around 50% to 51% and 49% to 50% in Area 3. The next step was to find the cycles-to-failure of each depth of discharge according to the properties of batteries. In this research, LiFePO4 battery were studied. By using the information from manufacturers, the total battery life fraction consumed could be calculated by dividing the number of cycles at depth of discharge d and thus the lifetime could be estimated by equation (18).

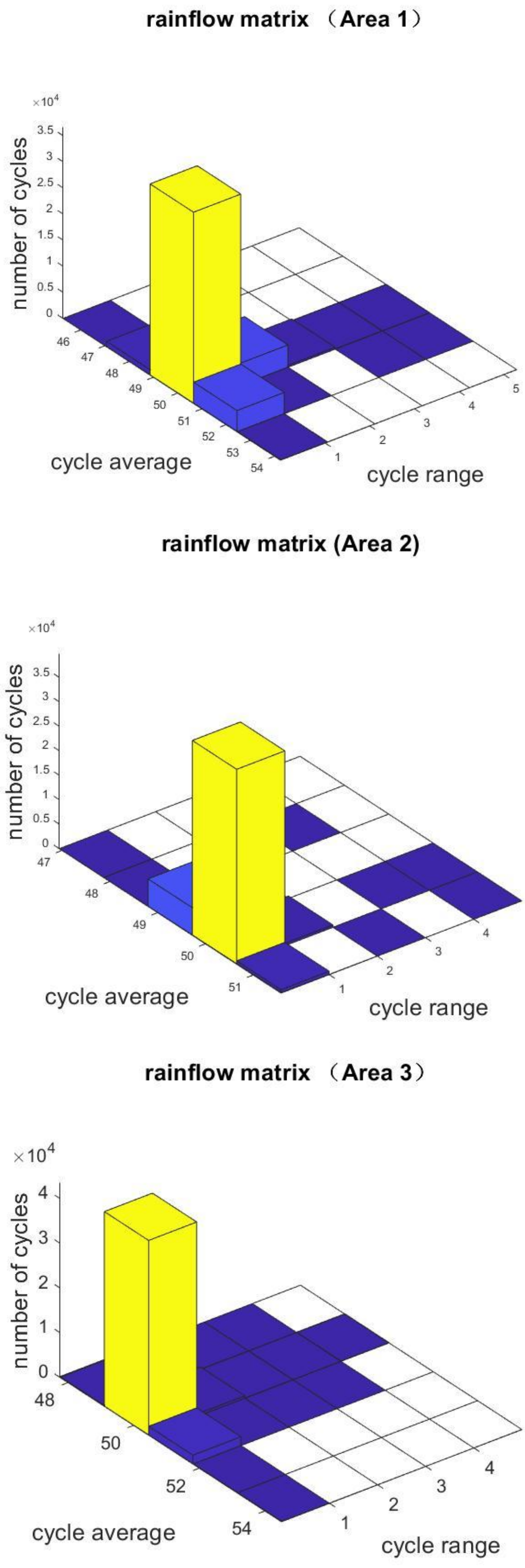


Fig. 30 Rain-flow counting of each failure at depth of discharge *d* for a year.

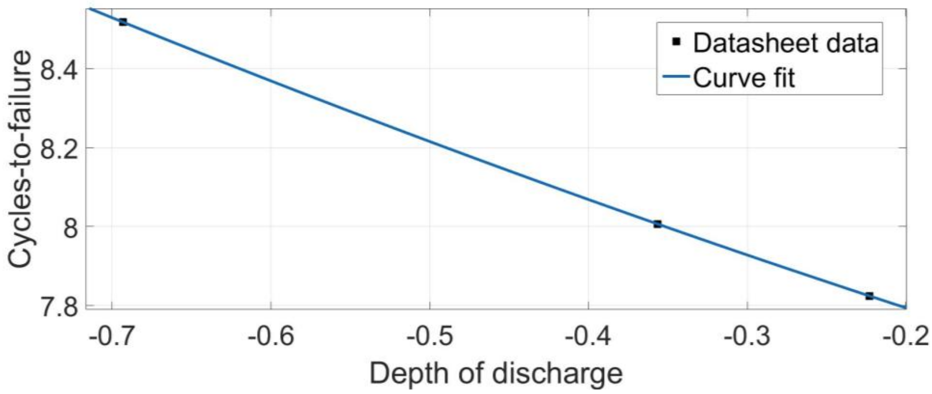
A typical Manufacturers' datasheet is shown in Table 9. Since it does not contain information of cycles-to failure with range less than 50% Depth of Discharge (DOD), an extrapolation of the manufacture's data was generated as a straight line on a log/log scale as shown in Fig. 31 [47] . Numerical curve-fitting gave the relationship of cycles-to-failure and depth of discharge as follows:

$$C_d = a_1 d^2 + a_2 d + a_3$$
$$a_1 = 0.3251, a_2 = -1.177, a_3 = 7.545 \tag{19}$$

Thus number of cycles, N_i, at different depth of discharges, d, and cycles-to-failure, C_{di}, at different depth of discharge, d, are known. The lifetime of the batteries could then be estimated by using equation (18).

Table 7 LIFEPO4 battery cycle life [19]

Cycle Life (capacity≥80% of nominal)	
80% DOD	2500 cycles
70% DOD	3000 cycles
50% DOD	5000 cycles



(a)

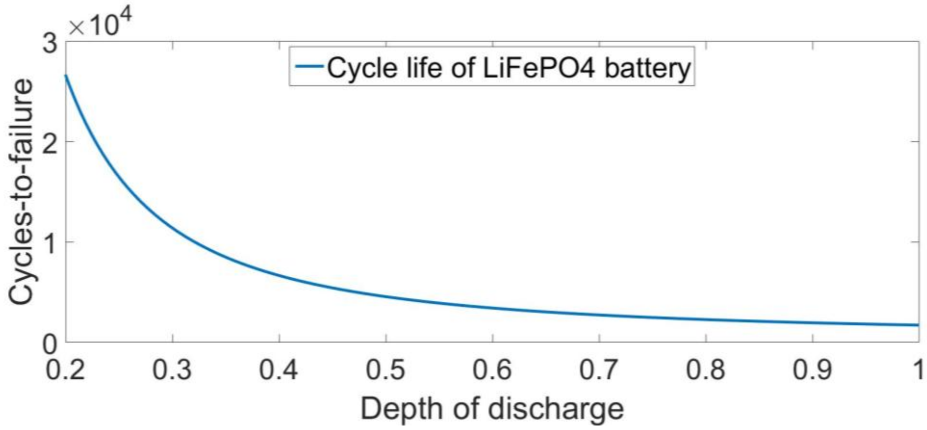


Fig. 31 (a) Cycles-to-failure versus depth of discharge in log/log scale for a LiFePO4 battery. (b) Extrapolated cycles-to-failure versus depth of discharge for a LiFePO4 battery.

By carrying out the calculation, the lifetime of each BESS was determined. It shows that the BESS in Area 1 is fully utilized and thus has a shorter lifetime, with 12 years. While the lifetimes of BESS in Area 2 and Area 3 from this calculation exceed the standard lifetime provided by the manufacturers, which is 15 years. Thus the lifetime of BESS in Area 2 and Area 3 was assumed to be 15 years, determined by their calendar life

5.1.3 Equivalent Annual Annuity (EAA) Evaluation

To evaluate the economic effectiveness of the BESSs, Equivalent Annual Annuity (EAA) was used. EAA is widely used to compare identical projects with unequal lives when considering the capital budgeting. Thus it is able to give the lifetime profit by calculating the constant annual cash flow. A project with higher EAA means that it is a more profitable choice.

EAA of the BESS installed in each area was computed as follows:

$$NPV = \sum \frac{C_t}{(1+i)^n} - initial\ investment \tag{20}$$

$$EAA = NPV \times \frac{r}{1-(1-r)^{-n}} \tag{21}$$

Where C_t is the net cash flow, i is discount rate, n is number of periods. It is reasonable to assume a discount rate to be 0.05 for a new technique [11]. Interest rate per period r is assumed to be 5% in this case. Net cash flow of a BESS consists of cash incomes and cash outgoings as illustrated in Table 8. The initial investment of a BESS as listed in Table 9 is made up of plant capital cost.

Table 8 BESS cash flow [13]

Income	
Frequency regulation service payments	£60/MWh
Outcome	
Buying electricity to charge batteries	£45/MWh
Fix O&M	£6.928/kW-yr
Variable O&M	£0.0012/kWh

Table 9 BESS initial investment [13]

Plant capital cost	
Power cost	£586.587/kW
Storage cost	£715.350/kWh

The EAA evaluation of each area is shown in Fig. 32. The highest EAA was achieved when the BESS was located in Area 1, with EAA of £4M, followed by Area 2 with £1.5M. Area 3 had the lowest effectiveness of BESS under £0.1M. Wind generation integration in Area 2 imposed uncertain generation fluctuations, which made the BESS installation profitable. In Area 3, pumped hydro generation coped well with fluctuating generation and load, installing a BESS here was less valuable than the other areas. In addition, charges for the use of the transmission system imposed additional costs. Furthermore, transmission losses occurred when transmitting BESS power from Area 3 to mitigate fluctuations in Area 1 and Area 2.

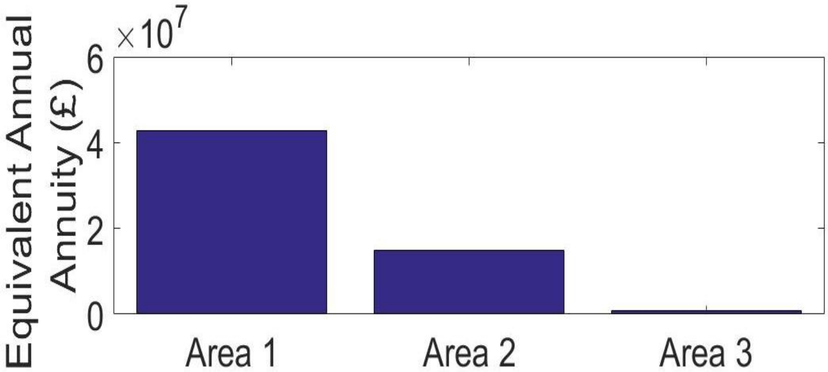


Fig. 32 Equivalent Annual Annuity evaluation of BESS installation.

CHAPTER 6: CONCLUSION & FURTHER WORK

6.1 Conclusion

This thesis has presented the performance and economic effectiveness of BESSs when used to supply frequency regulation in different locations in the UK. The dynamic simulation results show that system frequency was effectively improved with BESS installation. System frequency was improved the most when the BESS was in Area 1, with the most conventional generation and heavy load, when compared to the other two areas with wind generation and hydro generation. Rain-Flow counting results show that BESSs were more utilized in Area 1. The EAA of the BESS in Area 1 was also the best. The results show that the performance and economic effectiveness of BESSs varies in different network locations, which are affected by the generation/load fluctuations and generation mix of the area.

Lastly, this work is limited to a 12-bus system study to demonstrate the method. Further work will center on a more detailed model of the whole UK power system, to investigate the methodology's effectiveness in finding optimal sizing and location of grid-scale BESSs in the whole transmission network. However, the computing power requirements will be the biggest problem with that research.

6.2 Further work and recommendations:

- Optimal location site and size could be studied in a more complex system model with dynamic system behavior considering. Building a model of UK power system or a IEEE published standard system could give results that is more practically useful.
- Running generation/demand data for years to estimate the lifetime performance of BESSs would be a tough task and have a high requirement for the computing devices. Clustering algorism might be a way to find out the representative data set that lighten the

computing workload and leads to a reasonable result at the same time.

- Objectives for the optimizing the location and size of BESSs should be clear. It is known from previous work that bulk ESS achieve more economic value via saving cost in transmission capacity upgrade than saving operational cost of the system. Moreover, the objectives or the merchant energy owners and for the system operator is different. Merchant energy owners focus on the lifetime profit by providing system services. While the system operator will look for savings in transmission deferral, maintaining system stability etc. Thus further careful consideration is needed.
- After defining the objectives that BESSs aim to achieve, there is a number of optimisation technologies to choose from. Different optimisation method might lead to a different result. Results from optimisation should be investigated to find out the underlying cause of the result thus choose a realistic optimisation method.
- As the renewable generating capacity is increasing, introducing the dynamic model of wind farms to the power system dynamic model is essential. Solar power does not have a significant impact in this research, because the amount of solar power in the UK is small and solar power does not participate in frequency regulation due to its technology at the state of the art. In the current system dynamic model, wind generation was regarded as a negative load in this research, thus did not participate in the frequency regulation. Research for wind to supply synthetic inertia is under way, it can be foreseen that wind will participate in frequency response and contribute to system inertia for a while when frequency events occur once this technology matures. And introducing BESSs to the power system in turn can improve wind curtailments. Typically, the actual wind out-turn is lower than the day-ahead forecast value. In the actual practice, wind curtailment is an intentional reduction by the system operator to maintain the system stability. Also in some cases, wind power is curtailed due to the transmission constraints and system non-synchronous penetration. Since BESSs can help maintain the system stability and release transmission constraints, wind power does not necessarily have to be curtailed in the cases mentioned above. However, using batteries to save wind curtailments and transmission capacity expanding cost is at the price of reducing the lifetime of batteries

or requiring larger capacities of batteries. It means that if the wind dynamic model is introduced, then the control strategy of BESS might need to be reconsidered. Control strategies of BESSs differ for different purposes. For a BESS owner, the priority of using batteries is to get the most benefit from electricity arbitrage and providing regulation services with the least cost. However, from the perspective of an owner of a wind farm with BESS, saving wind curtailments will also be a benefit and that would affect the way they use the batteries. For example, they might want the batteries get charged when the wind level is higher than usual. And from the perspective of national grid or government, social welfare might be their main concern. Then batteries are likely to be used to main the system stability, improving wind curtailments to reduce electricity price, and to release transmission congestion, instead of electricity arbitrage. Thus according to different uses of batteries, different control strategies would apply.

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APPENDIX

Appendix A: Model parameters

Coal Power Plant	
R	0.72
Pref	0.341
Tg	0.2
Tch	0.3
H1	3.83
Gas Power Plant	
R	1.3
Pref	1.39
Tv	0.5
Ttd	0.5
Temp	0.14
Tn	0.22
Td	0.5
Tthcp	0.5
H2	6.28
Pumped Hydro Storage	
Tch	5